Audio-Visual Wireless Streaming Platform for the Residential Environment Employing Mesh and MIMO Extensions

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***Abstract*— ASTRALS is a project funded by the FP6 IST program which focuses on the in-home delivery, adaptation and processing of multiple audio/visual streams. One aspect of this project focuses on the wireless transmission of these streams using the IEEE 802.16 standard. A premium Quality of Service and IP based transmission scheme is employed in this project including MIMO and mesh extensions for increased throughput and robustness. The MIMO architecture is based on a novel technique which maximises the performance over both Line-of-Sight and non-Line-of-Sight conditions. On the other hand, mesh networking is responsible for multi-hopping transmission when a direct link is not available. This paper contains a number of simulation results which imply the possibility towards fully deterministic wireless audio/visual transmission in the home environment.**

I. Introduction

ASTRALS (Audio-visual STReaming plAtform for domestic Leisure and Security) is a project under the FP6 IST programme focusing on personalized, scalable, Audio/Video (A/V) encoding, trans-coding/trans-rating, storage and distribution in existing households via streaming optimised wireless links. A wireless platform that supports the robust and reliable audio-visual streaming based on the WiMAX standard is proposed in this paper [1]. A novel platform architecture comprising enhanced and optimised features is presented and its performance is evaluated via simulation results.

The IEEE 802.16 standard was chosen as a viable solution for the wireless video delivery due to its native Quality of Service (QoS) capabilities. The central notion of connections allows for several levels of QoS differentiation which are in turn implemented by a wireless network scheduler. This notion of connections also allows direct source-to-destination addressing between two Ethernet buses through wireless hops. These features clearly outperform the WiFi (IEEE 802.11) technology which is never QoS deterministic through the Wireless Multimedia Extensions (WME), and has limited addressing capabilities.

Additionally to the basic wireless platform an investigation is also conducted on the enhancement of the above streaming technology with MIMO and mesh networking extensions. These technologies are well known to provide significant improvements in the capacity and the link budget of wireless systems; however, there is still very little information available on their practical performance enhancement under realistic propagation conditions.

The MIMO scheme proposed in this paper aims at improving the system capacity especially in Line-of-Sight (LoS) while maintaining an equivalent performance to standard systems in non-LoS conditions. To achieve this, specifically designed antenna arrays are employed using a novel array design method that orthogonalises the MIMO channel response [2], [3]. A number of simulation results validating the superiority of this architecture are presented in this paper.

Another technique which achieves link budget and throughput improvements without sacrificing the wireless robustness is also presented in this paper. This corresponds to the IEEE 802.16-2004 mesh-mode which takes advantage of the attractive features of mesh networking such as self-organization, self-configuration, and self-correction to enable flexible integration, quick deployment, and easy maintenance at a low cost. With mesh networking, the wireless coverage can be extended by multi-hop communication which involves routing through Remote Stations (RSs). Moreover, spatial reuse is also possible in mesh networking as the communication between RSs is allowed without the need for an Access Station (AS).

The feasibility of the IEEE 802.16-2004 mesh-mode based on distributed coordinated scheduling in supporting real-time audio-visual streaming applications is evaluated via a commercial network simulator, i.e. QualNet [4]. Using simulation data it is shown that, in the absence of IEEE 802.16-2004 PMP-mode, the mesh-mode can be used to ensure viable wireless communication in home networks.

II. ASTRALS Architecture

The ASTRALS optimized A/V wireless home network platform is based on the modern and powerful wireless features of the IEEE 802.16-2004 standard, and in particular the Point-to-Multipoint (P-MP) mode. In detail, the ASTRALS wireless A/V home network uses a complete Ethernet-based platform prototype comprising:

- A central node called the AS which manages the wireless link connections
- Several RSs
- A system configuration, control & monitoring module

A block diagram of the wireless network architecture is shown in Fig. 1. The wireless subsystem can be connected to the Residential Gateway (RG), which operates as the AS. Moreover, it can be connected to several other pieces of equipment such as peripheral Set Top Boxes (STB) for video distribution or directly to an ASTRALS A/V extension sub-system. The optimized A/V streaming wireless platform is considered as an alternative communications network that may coexist with other wireless links (e.g. IEEE 802.11b/g). The architecture outlined above is used as the base scenario for MIMO and mesh networking studies, presented in the following paragraphs.

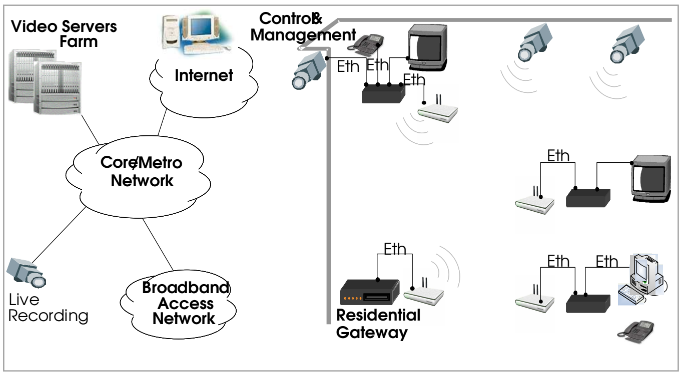

Fig. 1 ASTRALS home network architecture

III. ASTRALS Main Wireless Platform

The following figure (Fig. 2) shows, in more detail, the wireless network as implemented within the context of ASTRALS. The AS is connected to the Residential Gateway and each RS is connected to home devices. The transported video streams are mapped on a single connection each, based on strict QoS parameters such as latency, data rate, ARQ (Automatic Request Query), etc. Therefore, should, for example, an FTP transmission start from a PC, the video stream from the surveillance video camera and the video stream from the A/V server would not be affected.

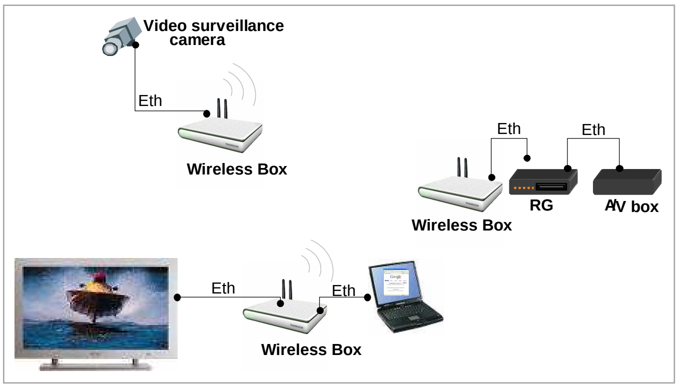

Fig. 2 ASTRALS wireless network architecture

The platform can be considered as a combination of a wireless and wired Ethernet networks where the wireless network remains a P-MP centralised topology. The Physical layer originates from the IEEE 802.16d standard with proprietary add-ons in order to improve the robustness of the wireless link.

The Scheduler has been specifically designed to address the home network requirements and is dimensioned by the transport of video and audio streams mainly located at the AS. On the other hand, the Classifier is both located at the AS and at the RS sides and allows the classification following several criteria as the source and destination addresses, the protocol types, the port numbers… etc. Finally, a highly efficient MAC layer has also been designed in the context of ASTRALS providing an efficiency of approximately 90%.

IV. ASTRALS MIMO Extension

Given the increasing demand for higher spectral efficiencies, MIMO technology is expected to be incorporated in IEEE 802.16 systems as a method for providing additional capacity. The MIMO extension employed in ASTRALS is based on a Spatial Multiplexing (SM) scheme that relies on transmitting independent data streams from each transmit antenna. Under specific propagation conditions, the throughput in a MIMO system employing this scheme increases linearly with the minimum number of transmit and receive antenna elements [5]. One example where this increase can occur is a (non-LoS) rich-scattering environment, where a large number of independent communications paths exists between the transmitting and receiving antenna elements.

When a LoS signal is present however, the performance of SM-MIMO systems is limited due to the high correlation between received signals [6]. Since the probability of a LoS signal is very high in a home environment, specific antenna arrays are employed in ASTRALS so that the orthogonality between the received signals is preserved [2], [3].

A. Full-Rank LoS Communications

The aforementioned LoS-optimised antenna arrays not only overcome the problem of excessive correlation but also result in capacities higher than that of rich-scattering environments [2], [3]. For the special case of Uniform Linear Arrays (ULAs) at both ends of a MIMO system a simple criterion has been derived that defines a number of array architectures with full-rank LoS responses. This is expressed by the following equation for a system with N_t transmit elements and N_r receive elements

$$s_1 s_2 \approx \lambda\left(\frac{1}{N_t}+r\right)\frac{D}{\sin\omega\sin\theta}, r\in \mathbf{Z}^+ \qquad \textbf{(1)}$$

In (1), $\mathbf{Z}^+$ corresponds to the set of positive integers and the angles ω and θ correspond to the geometry of Fig. 3.

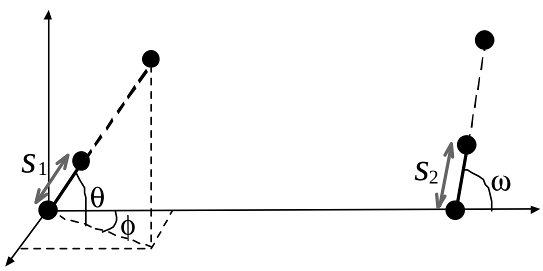

Fig.3 Uniform Linear Array orientations

B. Channel Model

In order to investigate the performance of MIMO systems in LoS a suitable channel model is required. It is common for the MIMO channel response matrix to be modelled as

$$\mathbf{H} = \sqrt{\frac{K}{K+1}}\mathbf{H}_{LOS} + \sqrt{\frac{1}{K+1}}\mathbf{H}_{NLOS} \qquad \textbf{(5)}$$

where H_{LOS} is the matrix containing the free-space responses between all elements, H_{NLOS} accounts for the scattered signals and K (i.e. the Ricean K-factor) is equal to the ratio of the powers of the free-space and the scattered signals.

In free-space, the complex response between a transmit element q and a receive element p is equal to $e^{-jkdp,q}/d_{p,q}$ (where k is the wavenumber (equal to $2\pi/\lambda$) and $d_{p,q}$ is the distance between the two elements). Thus, H_{LOS} is totally deterministic and depends only on the distances between each transmit and receive element. On the other hand, the response of the scattered signals is not deterministic and is usually modelled as a stochastic process. In this study H_{NLOS} is modelled as a $\mathbf{C}^{Nr \times Nt}$ matrix with normally distributed, zero mean i.i.d. elements of unit variance.

C. PER Performance of the Proposed and Standard Systems

For this study a Monte-Carlo simulation was performed using a physical layer 802.16 MIMO model based on [7], [8]. The PER performance of the proposed and standard methods was investigated for a number of values of the Ricean K-factor using MIMO channels generated from the combined stochastic/geometric channel model described in the previous section. The results for the LoS-optimised (ASTRALS) and standard MIMO systems are presented in Fig. 4-5 respectively.

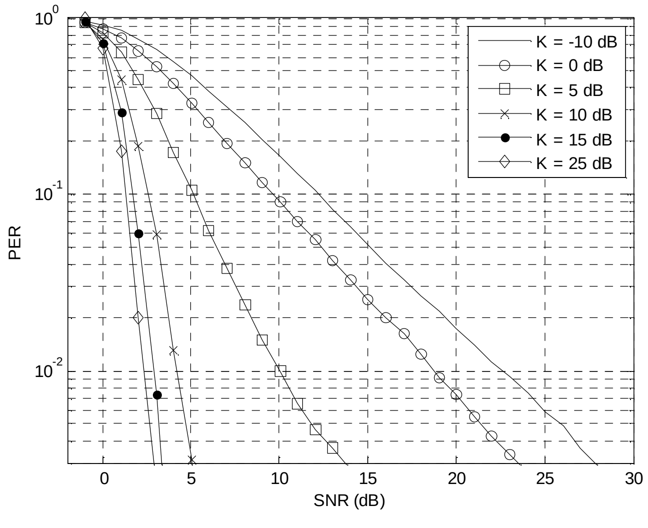

Fig. 4 PER vs SNR for the ASTRALS MIMO system as a function of the Rician K-factor

It is obvious that when a strong LoS signal exists (i.e. for large values of K-factor) there is a huge performance enhancement associated with arrays designed following the ASTRALS architecture over standard systems. For example, in the case of the K-factor being equal to 15 dB the difference in the required SNR at a PER of 10^{-2} is more than 30 dB.

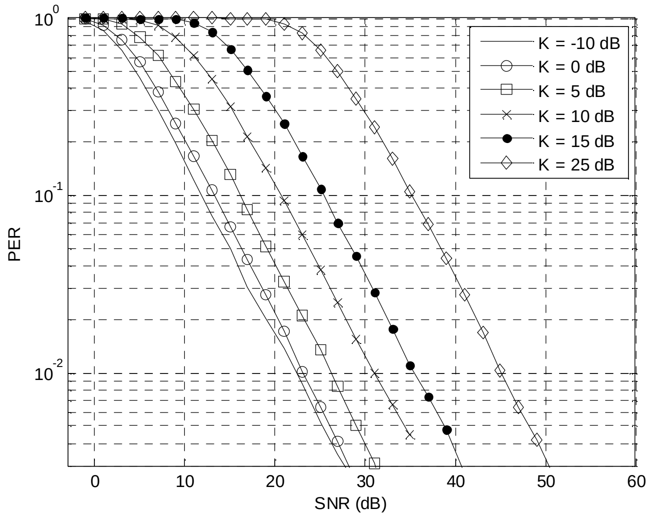

Fig. 5 PER vs SNR for the standard system as a function of the Rician K-factor

On the extreme of a very low K-factor the channel approaches the i.i.d. Rayleigh model that corresponds to a rich-scattering environment. This is also reflected in Fig. 4-5 where the PER curves for the case of K = -10 dB are identical for both systems (PER = 10^{-2} at SNR = 22.5 dB).

V. ASTRALS MESH EXTENSION

A. IEEE 802.16-2004 Mesh Mode

In the IEEE 802.16 mesh-mode the mesh AS plays a very important role in the network entry process. Mesh Network Configuration (MSH-NCFG) and Mesh Network Entry (MSH-NENT) messages are used for the advertisement of the mesh network, for assisting new nodes to establish coarse synchronisation and in subsequently joining the mesh network. The IEEE 802.16 standard proposes two scheduling mechanisms for facilitating TDMA-based communications in a mesh-mode; i.e. the centralized scheduling and the distributed scheduling. In the former, the mesh AS determines the resource (bandwidth) allocation for all mesh RSs in a centralised manner as in PMP-mode whereas traffic can be relayed by RSs through a multi-hop route. Overall, the centralised scheduling can be characterised as a simple method which however is usually associated with long connection setup delays [9].

In distributed scheduling, the allocation of data slots in the data sub-frame is performed by the RSs through the exchange of scheduling messages (i.e. MSH-DSCH) in the control sub-frame. MSH-DSCH messages are used for the coordination of the data slot requests and the allocation between two hop neighbours. Request-Grant-Grant Confirmation is a three-way handshaking mechanism proposed to setup a connection with neighbouring RSs. Each node must first compete for a control slot access using a pseudo-random election-based transmission timing (EBTT) algorithm. Based on this distributed EBTT algorithm and the scheduling information of its two-hop neighbours, each node can determine its transmission opportunities in the control sub frame independently and then periodically broadcast an MSH-DSCH.

The performance of the EBTT algorithm has been investigated by Cao et al [9] and Bayer et al [10]. Two fields, i.e. the demand level and the demand persistence are defined in an MSH-DSCH message for resource allocation purposes. However, there is no detailed information given on how these parameters should be set. Although the IEEE 802.16 standard defines signalling messages for distributed scheduling, the details of scheduling algorithm and data slot assignment scheme are left un-standardised. So far, no work has been performed on the evaluation of mesh-mode performance in supporting real-time audio-visual applications.

B. Simulation Model and Environment

In this paper, the IEEE 802.16-2004 mesh-mode was implemented in a QualNet network simulator. Even though a wide range of MAC protocols (including IEEE 802.11 and IEEE 802.16-PMP mode) are modelled in this software, an IEEE 802.16-mesh mode is not yet available so a new MAC module was implemented as part of this project. This new module implements the control message exchange for network configuration (MSH-NCFG) procedure, node entry (MSH-NENT) procedure, and the distributed scheduling (MSH-DSCH). The EBTT algorithm, three-way handshaking mechanism and data channel allocation were also implemented in the model. In detail, a simple first-come first-served resource allocation scheme was implemented, in which, the receiver grants the bandwidth allocation to the requests according to their arrival sequence and based on the availability of resources.

Demand persistence of one and seven are supported in this model where a demand persistence of one corresponds to the slots in one upcoming frame being reserved for data transmission whereas, a demand persistence of seven corresponds to the bandwidth being reserved for all upcoming frames until an explicit MSH-DSCH message is transmitted to cancel the reservation. All data transmissions are assumed to take place based on the distributed coordinated scheduling.

TABLE I
SIMULATION PARAMETERS FOR MESH SIMULATION

Parameter	Value
Simulation Area	50 m x 50 m
Number of Nodes	15
Number of Mesh AS	1
Channel Rate	54 Mbps
Frame Duration	10 milliseconds
Minislot Duration	0.04 milliseconds
NCFG Hold-off Exponent	0
DSCH Hold-off Exponent	0
Demand Persistence	7
Transmission Range	37 metres
Propagation Model	Path Loss with Log-Normal Shadowing

The main objective of this simulation study was to evaluate the performance of mesh networks in supporting audio-visual streaming application. The simulation parameters are listed in Table I. An area of 25m x 15m was simulated and 15 stations were deployed in the area as shown in Fig. 4, with mesh AS at the south-west corner of the house. Real-time video traffic from a public library of video traces was used as the traffic input [11]. Video traces of surveillance video were used in these simulations encoded using a H.263 codec with target bit rate of 256Kbps. The indoor path loss has been previously shown to obey the following distance power law [12]:

$$PL(dB) = PL(d_0) + 10\,n \log\left(\frac{d}{d_0}\right) + X_\sigma \qquad \textbf{(2)}$$

where the value of n depends on the surroundings and building type, and X_σ corresponds to a normally distributed random variable with a standard deviation of σ dB. Based on measurement data and suggestions by [13], different values of n were used for representing different indoor environments. For an indoor environment with unobstructed LoS path to the receiver, n was suggested to be between 2 and 3. For the case where the transmitter and the receiver are at the same level but separated by brick walls (obstructed path), n was found to be between 4 and 5. In these simulations, all stations were transmitting at 17 dBm of power and a carrier frequency of 5.2GHz. The path loss exponent was varied from 1.5 to 5, while the shadowing deviation, σ was set to 5 dB in all simulations.

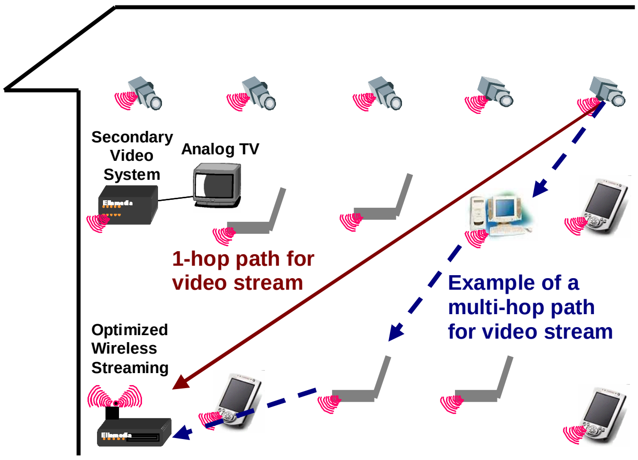

Fig. 6 Mesh simulation scenario

C. Simulation Results

Two sets of simulations were conducted. The first corresponded to one-hop communications between the mesh AS and RSs whereas the second corresponded to multi-hop communications following the distributed mesh-mode described earlier. A video stream of 256 Kbps was transmitted from a surveillance camera located at the north-east corner of the house to the mesh AS as shown in Fig. 6. The simulation was repeated with 100 different seed values whereas the path loss exponent, n, in the Path Loss model was varied from 1.5 to 5 to represent different indoor propagation environments.

The results are shown in Fig. 7 and demonstrate that one-hop communication was only feasible in indoor environments with a path loss exponent of less than three. For n equal to 3, the routing protocol could only manage to successfully establish a route in 22 out of the 100 simulation trials. When n was raised to more than three, the signal loss was so severe that it was almost impossible to form a one-hop route between the RS and the mesh AS.

In mesh mode, although the RS could not communicate directly with the mesh AS it could still route the route request to its peer RSs. The route request would be routed via multiple hops and eventually reach the mesh AS. The path could then be set up and multi-hop wireless communication enabled the video stream to be transmitted to the mesh AS. In detail, it was found that the communication was feasible in the mesh-mode where multi-hop routes could be formed even at large values of the path loss exponent (n = 5). This result clearly demonstrates that the IEEE 802.16-2004 mesh-mode can successfully complement the PMP-mode in coverage extension or in cases where the PMP-mode is not available or not accessible.

Fig. 8 shows the average length of the routes formed by the routing protocol based on the distributed coordinated mesh-mode. As the propagation conditions became worse, only short-range wireless communications were feasible in the home environment resulting in an increased average path length with increased in path-loss exponent.

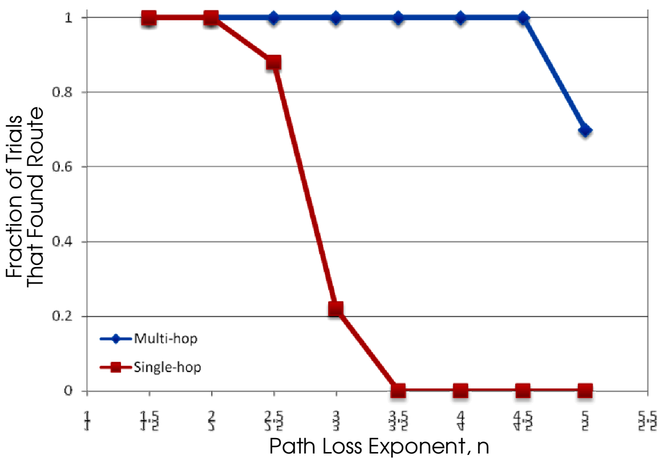

Fig. 7 Success ratio in finding route for different n

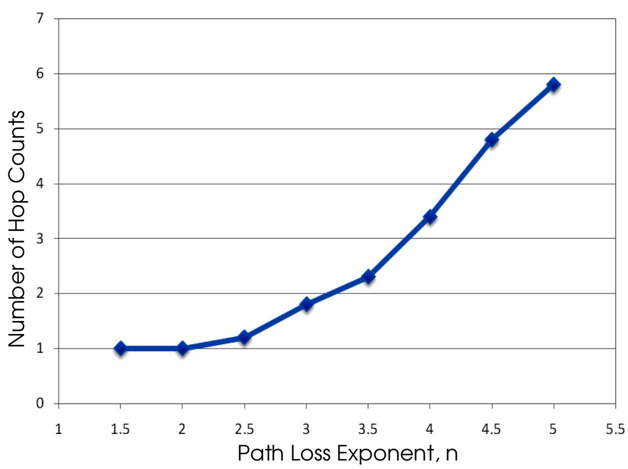

Fig. 8 Average length of multi-hop routes for different n

VI. CONCLUSIONS

In this paper, the feasibility of in-home wireless transmission was studied, which is known to remain a challenging area when targeting fully deterministic coverage. The project involved work on MIMO with domestic channel profiles, and in particular with the unfavourable case of LoS propagation as an inevitable propagation situation in short indoor communications. Simulation results have shown a very significant SNR performance enhancement of the proposed architecture over standard MIMO systems on the order of 30 dB in strong LoS conditions (K = 15 dB). Another drastic improvement was also presented for mesh networking using values of the path-loss exponent common to a home environment. In detail, mesh networking has been shown to significantly improve the chance of communication between two nodes via multi-hopping. Future work will focus in evaluating the performance of mesh-based home networks in terms of throughput, end-to-end delay and jitter, which are important QoS parameters to support multiple video-streams. As shown in this paper, there is already a consensus emerging suggesting that the an IEEE 802.16 baseline system incorporating MIMO and mesh extensions can allow the deployment of a fully deterministic wireless in-home network supporting QoS-guaranteed delivery of multiple video-streams.

ACKNOWLEDGMENT

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