MIMO Channel Modeling for Integrated High Altitude Platforms, Geostationary Satellite/Land Mobile Satellite and Wireless Terrestrial Networks

Aamir Habib and Qamar-ul-Islam

***Abstract*—In this work we analyze first the channel models associated with an integrated High Altitude Platform (HAP), satellite and terrestrial networks and then apply multiple antenna systems to evaluate and investigate the gains that can be achieved by using MIMO techniques on such networks. We first take into account scenarios consisting of GEO satellite and few HAPs and then LMS with HAPs and construct a MIMO channel model. Subsequent to the application of such multiple antenna techniques we find the parameters that are most critical in system design and evaluate the performance advantages of such systems over conventional integrated Satellite and terrestrial only networks.**

***Index Terms*— High Altitude Platform (HAP), Multiple-Input Multiple Output (MIMO), Channel Modeling, Cross Polar Dicrimination (XPD), Land Mobile Satellite (LMS).**

I. Introduction

Multiple-Input Multiple-Output (MIMO) refers to a wireless communication system where at both sides of the communication link more than one antenna is applied [1–3]. The MIMO approach promises a significant increase in the system capacity and availability of communication links in a multipath propagation environment. The approach is an extension of diversity principles often applied in RF radio links to improve link reliability. Combining the transmit and receive diversity results in a new concept, which not only increases the link reliability but also offers a potential to increase the radio link capacity. The MIMO concept can be used for three different objectives which can be used to:

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Aamir Habib is with the Electrical Engineering Department I, Institute of Space Technology, Islamabad, Pakistan. (phone: 0092-51-9075489; fax: 0092-51-9273310; e-mail: aamir.habib@ ist.edu.pk).

Qamar-ul-Islam is with the Electrical Engineering Department I, Institute of Space Technology, Islamabad, Pakistan. (phone: 0092-51-9075428; fax: 0092-51-9273310; e-mail: qamar.islam@ ist.edu.pk).

1) Increase the capacity of communication link by using Spatial Multiplexing
2) Improve the availability of communication link by applying Spatial Diversity
3) Use of beamforming for Interference Cancellation

A. HAP and satellite networks

With an ever increasing demand for capacity for next generation multimedia applications, service providers are looking for novel, reliable and cost efficient ways to deliver wireless communications services. In developed countries we are familiar today with seeing Base Stations for mobile phone services dotted around the countryside, but these can be expensive to deploy and maintain for continual provision of service. This patchwork of coverage delivers cellular communications, an efficient way of delivering through spectrum reuse.. This concept is widely adopted with a number of technologies, including the 2G and 3G mobile systems, but also new technologies such as WiMAX, LTE and also Wi-Fi, where in this latter case islands of coverage (hot-spots) are provided.

An alternative for sparsely populated rural environment or less developed areas is to use satellite communications. Satellites today are increasingly sophisticated, and capable of delivering spot beam coverage, with minimal ground infrastructure. However, they are incapable of matching the high-capacity densities seen with terrestrial infrastructure.

A possible third alternative way of delivering communications and other services is to use high altitude platforms (HAPs). HAPs are either airships or planes, which operate in the stratosphere, 17–22 km above the ground [4, 5]. Such platforms will have a rapid roll-out capability and the ability to serve a large number of users, using considerably less communications infrastructure than required by a terrestrial network [6]. Thus, the nearness of HAPs to the ground, while still maintaining wide area coverage, means that they exhibit the most promising features of terrestrial and satellite communications. We will explore these benefits in more detail in later sections.

The main aim of HAPs is to provide quasi-permanent high data rate, high capacity-density communications provision over a wide coverage area, ideally from a fixed point in the sky. In practice due to aeronautical constraints all HAPs present compromises. It is helpful to specify the following HAP 'vital' statistics, and as we shall see, these may radically affect the communications system design and ultimate capabilities:

1) Volume, payload power and mass
2) Attitude control and station keeping
3) Endurance

HAPs can be divided into four categories namely,

1) Manned plane, e.g. Grob G520 Egrett [9]
2) Unmanned plane (fuel), e.g. AV Global Observer [10]
3) Unmanned plane (solar), e.g. AV/NASA Pathfinder [11]
4) Unmanned airship (solar), e.g. Lockheed Martin HAA [12]

B. *MIMO in High Altitude Platform (HAP)*

The traditional MIMO method in HAP broadband communication systems has partial applicability due to channel being mainly Line Of Sight (LOS) channel conditions, weakly spread communication channel, directional antennas, allocated frequency bands and relatively small size of the platform. However, two or more platforms can be placed in an arrangement and organized by inter-platform links can communicate to a multi-antenna system on the ground, thus forming a virtual MIMO system.

The study in [7] investigates a virtual MIMO (V-MIMO) approach, based on an assemblage of multiple HAPs, providing broadband wireless access to a combined terminal with multiple antennas which are placed on fast moving trains under principally LOS propagation surroundings. Due to the effect of random blocking or shadowing of the platforms caused by train operating environment, the channels toward individual HAP are statistically independent, yielding some diversity or multiplexing gain. In particular, Alamouti and extended Alamouti schemes are investigated, using fixed wide-lobe receive antennas, and compared with the reference receive diversity design relying on selecting best HAP that needs highly directional and moveable antennas. The conceptual system architecture making use of the V-MIMO approach in the HAP system is depicted in **Fig. 1**. The system architecture in **Fig. 1**. comprises of,

1) A set-up of HAPs, positioned above the main railway lines and linked by error free inter-platform links
2) One or more ground stations connected with HAPs by fixed backhaul links and hosting gateways to external networks and/or application servers
3) Cooperative terminals mounted on the train and acting as intermediary nodes to the local wired or wireless system and HAP communication system

The constellation can be used to investigate the possibility of using V-MIMO with comprehensive Alamouti code for alleviation of shadowing effects in a predominantly LOS mobile environment [7], however considering the switched 3-state channel model. The performance of the following three diversity schemes has been evaluated and compared:

1) Selection diversity approach, where the user terminal chooses the best accessible HAP
2) V-MIMO approach based on the Alamouti code transmitted from two HAPs
3) V-MIMO approach based on the extended Alamouti code transmitted from four operating HAPs

The performance evaluation shows that the use of Space Time Block Coding (STBC) diversity schemes in HAP communication systems can be applied with an objective to mitigate shadowing and blocking in a LOS propagation environment [7]. Applying two and four transmit antennas (HAPs) considerably outperforms a scheme based on the selection of a single HAP. Nevertheless, even though link outage probability is reduced considerably, it cannot be eliminated entirely due to high rise structures, tunnels, and/or the potential presence of a large rain cell with heavy rainfall in the case of using higher frequency bands.

In satellite communication systems with similar propagation environment as in a HAP communication system, the MIMO approach seems to be applicable by applying two MIMO concepts. These are: the concept of cooperative diversity and the notion of polarization space–time coded diversity (PCT) [8]. The idea of polarization coded diversity is making use of the differences of orthogonally polarized radio waves at reflection, refraction and diffraction. It promises fourfold diversity gain and twofold increase in the capacity by applying double polarized transmission and reception, and six fold diversity gain and twofold increase in the capacity by applying 3D polarized receive antennas [8]. The results published in [8] assume the omnidirectional antenna is applied at the user terminal and directional patch antenna at the satellite. Moreover, the surroundings at the user terminal is highly scattering with poor LOS component. Such a scenario may occur if the user terminal is located indoors or shadowed by trees and moving at high speed. However, the allocated frequency bands for broadband HAP communications are in the millimeter frequency band, which forces the use of mostly outdoors mounted directional antennas, resulting in a low scattering propagation environment. Thus, cooperative diversity seems the only possible solution to use in the MIMO approach in the broadband HAP communication system.

II. MIMO CHANNEL MODEL

A system of multiple platforms forming a network of cooperating nodes, each of them equipped with a single antenna, can be viewed as a single Base Station (BS) equipped with multiple antennas. Provided the platforms are spaced sufficiently apart from each other, such a HAP network guarantees independent propagation paths, even in a pure LOS channel. A system formed in this manner is referred to as a Virtual MIMO (V- MIMO) system and enables the exploitation of all the benefits offered by conventional MIMO systems. We analyze the channels for various scenarios and arrangement with different architectures.

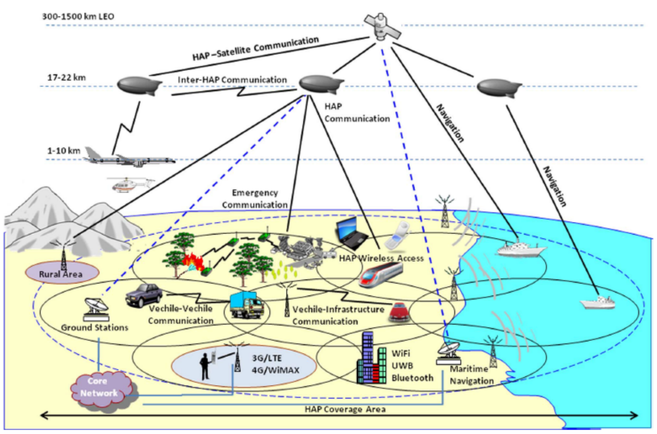

Fig. 1. Theoretical structure for future communication infrastructure based on terrestrial/HAPs/satellites integration

HAPs can be arranged in various different configurations. The advantages and issues would directly depend upon the overall system architecture. We have divided the scenarios in six different architectures. Application of MIMO and V-MIMO are discussed with emphasis on the type of channel model encountered,

1) Standalone HAP system
2) Multiple HAPs design
3) Integrated terrestrial/HAPs design
4) Integrated satellite/HAPs design
5) Integrated terrestrial/HAPs/satellites configuration
6) Multilayer approach for integrated scenarios

1) Standalone HAP Configuration

The major applications of standalone HAP configuration, depicted in **Fig. 2.**, include emergency communications, disaster relief management system, short-term events, and large-scale high-demand speckled events such as Olympic Games or World Cups. The platforms can assist users directly, but usually they will be connected to an external network system through a access [13].

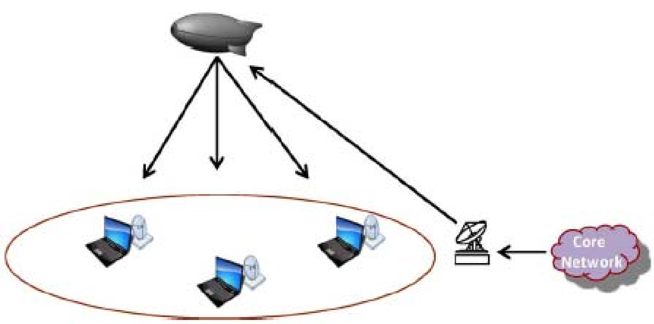

Fig. 2. The standalone HAP configuration for a specific coverage area.

This is the simplest of scenarios that can be used for communications. Application of MIMO would not enhance any performance due to mainly line of sight communications. Independent paths are difficult to be generated leading to a rank deficiency of the MIMO channel matrix. Even if we are able to put multiple antennas at the HAP's, the distance between the antennas would be such (low) that it will not give any worthwhile performance gains. Spatial diversity may not be able to be achieved.

The method we follow to model the propagation from the HAP to the terminal considers the multipath and the shadowing effects, being the resulting channel as narrowband. Considering these assumptions in mind and considering dual-polarized HAP and dual-polarized antennas at the terminal, the most easily apprehended scenario results in a 2 X 2 MIMO channel given below as

$$\mathrm{H} = \begin{bmatrix} \mathrm{h}_{11}^{11} & \mathrm{h}_{12}^{11} \\ \mathrm{h}_{21}^{11} & \mathrm{h}_{22}^{11} \end{bmatrix}$$

where h_{ij}^{kl} denotes the channel gain between the i th polarization of the kth receiver antenna and the jth polarization of the l th satellite antenna [16][17]. The dual polarized system can be achieved by deploying Left Hand Circularly Polarized (LHCP) and Right Hand Circularly Polarized (RHCP) antennas. The channel can be further divided into two parts as follows

$$\mathrm{H} = \overline{\mathrm{H}} + \widetilde{\mathrm{H}}$$

$$h_{ij}^{kl} = \left|\overline{h}_{ij}^{kl}\right| \exp\left(\overline{\phi}_{ij}^{kl}\right) + \left|\widetilde{h}_{ij}^{kl}\right| \exp\left(\widetilde{\phi}_{ij}^{kl}\right)$$

where $\overline{\mathrm{H}}$ is used for shadowing and $\widetilde{\mathrm{H}}$ for the multipath effect. The phases given by $\overline{\phi}_{ij}^{kl}$ and $\widetilde{\phi}_{ij}^{kl}$ are uniformly distributed over the interval [0,2π]. The envelope $\left|\overline{h}_{ij}^{kl}\right|$ is log-normally distributed with mean α and standard deviation ψ and the envelope $\left|\widetilde{h}_{ij}^{kl}\right|$ is Rayleigh distributed with average power *MP*.

2) Constellation of Multiple Interconnected HAPs

To expand the coverage and/or capacity of a HAP-based communication system, a network of multiple HAPs can be deployed, where HAPs are joined together via ground stations or, in case of HAPs with switching payload capabilities, by inter-platform links (IPLs). The latter brings in the new element for investigation compared to the previous architecture, which due to the operating environment can make use of either microwave or optical links. While IPLs notably increase the complexity of the payload, they significantly reduce the system requirements for the ground segment by providing system support independent of terrestrial networks, and provide flexibility in system requirements and improved coverage especially in remote areas [14]. However, they are limited by onboard processing systems and power constraints. (Refer to **Fig. 3**.).

As an example we consider three HAP stations installed with dual polarized antenna each. Communication is done only between HAPs and ground station. The ground stations are equipped with also two antennas. The MIMO channel formed would then be a 6 X 2 MIMO. Polarization diversity can be used in this scenario. Both Non Line Of Sight (NLOS) and LOS channel can be modeled or a combination of both. As we are using polarized antennas the effect of antenna XPD and channel XPD would be an important parameter to consider. HAPs are also separated by some distance. Another situation could be three HAPs installed with single antenna element each. Ground station is equipped with two antennas. MIMO channel formed is as a Virtual MIMO due to separation by some distance, which is important for V-MIMO. A 3 X 2 MIMO Channel model is formed.

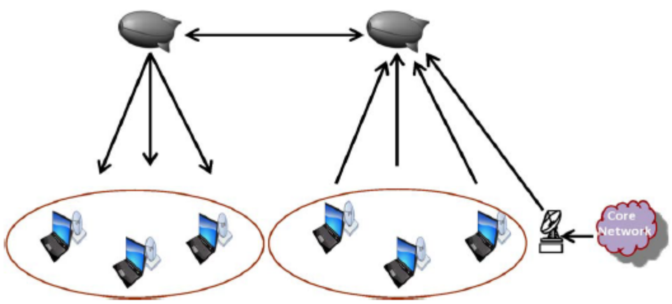

Fig. 3. A constellation of multiple interconnected HAPs

An example for this system is given for high speed communication in trains as shown in **Fig. 4.** For the **Fig. 4.** we construct the channel model as an example taking into account all the channel parameters. We consider a single antenna at each HAP and same number of antennas on the train as on each HAP. The inter HAP link is established through separate directional antennas on each HAP. The channel between HAP can itself become a LOS MIMO channel. In another configuration one of the HAPs can become central unit and all other can communicate with it through an antenna network. This central HAP is made responsible to communicate with ground station. The Virtual MIMO channel model for downlink from HAP to train would be,

$$\mathrm{H}=\begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}$$

Now if we assume that the antennas at each HAP and ground terminal at the train are equipped with dual polarized antennas then XPDs have to be taken into consideration. XPD of antennas are defined as follows

$$XPD_{ant}=10\log\left(\frac{E\left\{\left|h_{ii}\right|^2\right\}}{E\left\{\left|h_{ij}\right|^2\right\}}\right)$$

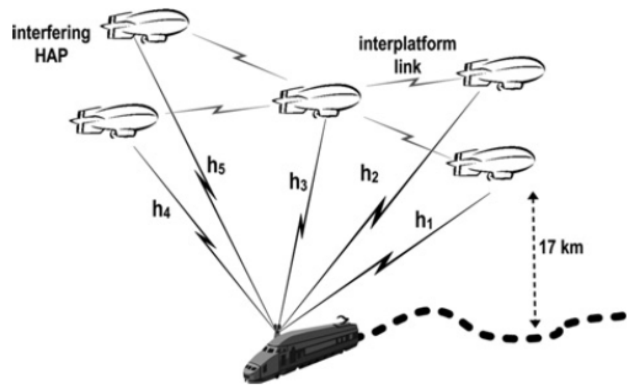

Fig. 4. Virtual MIMO System

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Now the MIMO matrix with polarization and small scale fading effects would be given by,

$$\begin{bmatrix} E\{|\tilde{h}_{11}^{11}|^2\} & E\{|\tilde{h}_{12}^{11}|^2\} & E\{|\tilde{h}_{13}^{11}|^2\} & E\{|\tilde{h}_{11}^{12}|^2\} & E\{|\tilde{h}_{12}^{12}|^2\} & E\{|\tilde{h}_{13}^{12}|^2\} \\ E\{|\tilde{h}_{21}^{11}|^2\} & E\{|\tilde{h}_{22}^{11}|^2\} & E\{|\tilde{h}_{23}^{11}|^2\} & E\{|\tilde{h}_{21}^{12}|^2\} & E\{|\tilde{h}_{22}^{12}|^2\} & E\{|\tilde{h}_{23}^{12}|^2\} \\ E\{|\tilde{h}_{31}^{11}|^2\} & E\{|\tilde{h}_{32}^{11}|^2\} & E\{|\tilde{h}_{33}^{11}|^2\} & E\{|\tilde{h}_{31}^{12}|^2\} & E\{|\tilde{h}_{32}^{12}|^2\} & E\{|\tilde{h}_{33}^{12}|^2\} \\ E\{|\tilde{h}_{41}^{11}|^2\} & E\{|\tilde{h}_{42}^{11}|^2\} & E\{|\tilde{h}_{43}^{11}|^2\} & E\{|\tilde{h}_{41}^{12}|^2\} & E\{|\tilde{h}_{42}^{12}|^2\} & E\{|\tilde{h}_{43}^{12}|^2\} \\ E\{|\tilde{h}_{51}^{11}|^2\} & E\{|\tilde{h}_{52}^{11}|^2\} & E\{|\tilde{h}_{53}^{11}|^2\} & E\{|\tilde{h}_{51}^{12}|^2\} & E\{|\tilde{h}_{52}^{12}|^2\} & E\{|\tilde{h}_{53}^{12}|^2\} \\ E\{|\tilde{h}_{61}^{11}|^2\} & E\{|\tilde{h}_{62}^{11}|^2\} & E\{|\tilde{h}_{63}^{11}|^2\} & E\{|\tilde{h}_{61}^{12}|^2\} & E\{|\tilde{h}_{62}^{12}|^2\} & E\{|\tilde{h}_{63}^{12}|^2\} \end{bmatrix}$$

$$= MP\begin{bmatrix} 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \\ 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \\ 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \\ 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \\ 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \\ 1-\beta & 1-\beta & 1-\beta & \beta & \beta & \beta \end{bmatrix}\begin{bmatrix} 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \\ 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \\ 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \\ 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \\ 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \\ 1-\gamma & 1-\gamma & 1-\gamma & \gamma & \gamma & \gamma \end{bmatrix}.$$

where MP (dB relative to LOS), be the average power of the small-scale fading and γ and β are the cross-polarization discriminator factors. Specific values can be found as,

$$XPD_{ant}=10\log\left(\frac{1-\beta}{\beta}\right).$$

$$XPD_{env}=10\log\left(\frac{1-\gamma}{\lambda}\right)$$

The parameter γ takes into account the mutual coupling between orthogonal polarizations due to the scatters and is given by the antenna cross-polarization discriminator factor XPD_{ant} whereas the parameter β accounts for the antenna's ability to discriminate orthogonal polarization that is characterized by environment cross-polarization discriminator factor XPD_{env}. We assume here and in the subsequent discussions that the correlation matrices are negligible to be included in channel modeling. This assumption is quite valid as the separations between the HAPs and the antennas at the train are enough to de-correlate the signals. In the above matrices we extend the case of 2 X 2 MIMO to 6 X 6 MIMO by consider three 2 X 2 spatially separated dual polarized MIMO channels [18]. Now we consider the multiple antenna scenario between the inter-satellite links. If we consider one of the satellites as the one which has to eventually communicate with the ground station then a Virtual MIMO channel of size 4 X 1 will be formed as shown below,

$$\mathrm{H}_{\mathrm{ihap}} = \left[h_{11}^{ihap} \quad h_{21}^{ihap} \quad h_{31}^{ihap}\right]^T .$$

To handle issues of inter-satellite link is relatively straight forward but for downlink communication complexity arises as we increase the number of HAP's. All the data routing from central station and the train for downlink communication is routed first to the central HAP and then distributed to HAPs with inter-satellite link and subsequently to the train and similarly for the uplink. The critical path are as follows:

a) Distance between ground station and the central HAP
b) Distances between HAP's and the train.
c) Average spacing between the central HAP and the other HAPs

3) Integration of HAPs and Terrestrial Infrastructure

In the case of possible integration of HAPs and terrestrial infrastructure most efforts have been concentrated on the investigation of coexistence of 3G/4G services via HAPs and terrestrial networks. The main focal issue has been on coping up with the capacity or interference related impairments, resource allocation strategies, and the average performance in different areas of the integrated network. All these are critical topics to study for an efficient integration scheme. A typical investigated configuration is depicted in **Fig. 5**. The capacity of integrated HAP-terrestrial CDMA system with sharing band overlay configuration has been investigated in [15].

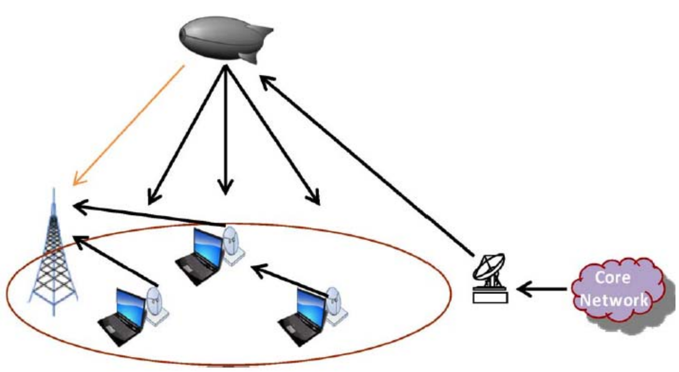

Fig. 5. HAP as an integrated element in the terrestrial infrastructure

Antennas at the HAP platform are normally directional antennas. They can be multiple antennas or single antennas depending upon the application. Many possibilities exist for the antenna combinations. We consider three combinations.

a) MIMO channel between HAP and Users (static/mobile)
b) MIMO channel between HAP and terrestrial Base Station(BS)
c) MIMO channel between HAP and Ground Station
d) Conventional MIMO between users and BS

MIMO channel between HAP and Users (static/mobile)

Assuming three antennas at the HAP spatially separated to avoid correlation and three users in the cell each with a single antenna. The Virtual MIMO matrix would be for this channel as follows,

$$\mathrm{H}_{\mathrm{HU}} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}.$$

MIMO channel between HAP and terrestrial Base Station.

Assuming three antennas at the HAP spatially separated to avoid correlation and the BS is also equipped with three antennas. The MIMO channel model would be as follows,

$$\mathrm{H}_{\mathrm{HB}} = \begin{bmatrix} h_{44} & h_{45} & h_{46} \\ h_{54} & h_{55} & h_{56} \\ h_{64} & h_{65} & h_{66} \end{bmatrix}.$$

MIMO channel between HAP and ground station

For this channel the model would be same as previously described assuming same antenna parameters.

$$\mathrm{H}_{\mathrm{HG}} = \begin{bmatrix} h_{77} & h_{78} & h_{79} \\ h_{87} & h_{88} & h_{89} \\ h_{97} & h_{98} & h_{99} \end{bmatrix}.$$

Conventional MIMO between users and BS

Assuming same number of parameters as in previous case the MIMO channel would be as follows,

$$\mathrm{H}_{\mathrm{UB}} = \begin{bmatrix} h_{\{10\}\{10\}} & h_{\{10\}\{11\}} & h_{\{10\}\{12\}} \\ h_{\{11\}\{10\}} & h_{\{11\}\{11\}} & h_{\{11\}\{12\}} \\ h_{\{12\}\{10\}} & h_{\{12\}\{11\}} & h_{\{12\}\{12\}} \end{bmatrix}.$$

The combined virtual channel taking into account all the individual models would be given as follows

$$\mathrm{H} = \left[\mathrm{H}_{\mathrm{HU}} \quad \mathrm{H}_{\mathrm{HB}} \quad \mathrm{H}_{\mathrm{HG}} \quad \mathrm{H}_{\mathrm{UB}}\right].$$

A similar treatment can be used as described in previous sections for modeling channels if dual polarized antennas are used at both the transmitting and receiving ends of communications.

4) Integrated Satellite/HAPs System

This first system design which involves HAPs and which are capable of providing accurate global connectivity is the one which is an integrated satellites and HAPs network. Fundamentally the HAP system acts as a wireless access loop to the global network. A typical configuration of integrated satellite/HAP system is illustrated in **Fig. 6**. The communication starts from the core network and data is routed to the satellite network through a ground station. The satellite network could be LMS or geostationary satellite system. The satellite network routes traffic through HAP platform which act as relay for communications to the users. Effectively the MIMO channel would be a three tier model.

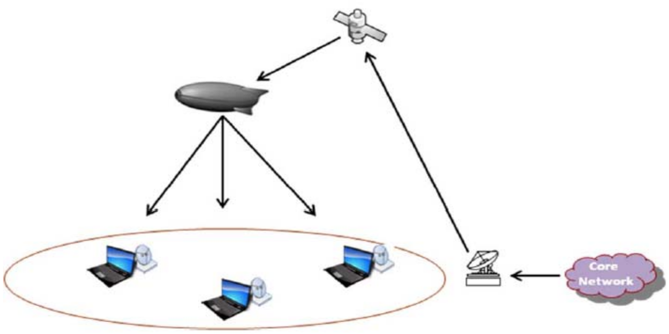

Fig. 6. HAP as the first/last mile of the satellite network in integrated satellite/HAP system.

The channel model would be quite similar to the one defined in the previous section. The main difference would be the channel added due to the direct link between the satellite and the ground station. Also as clear from the **Fig. 6**., as there are no links between the HAP and a base station, the overall model would be slightly simpler as given below,

$$\mathrm{H} = [\mathrm{H}_{\mathrm{HU}} \quad \mathrm{H}_{\mathrm{HS}} \quad \mathrm{H}_{\mathrm{SG}}],$$

where

$$\mathrm{H}_{\mathrm{HU}} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}, \quad \mathrm{H}_{\mathrm{HS}} = \begin{bmatrix} h_{44} & h_{45} & h_{46} \\ h_{54} & h_{55} & h_{56} \\ h_{64} & h_{65} & h_{66} \end{bmatrix},$$

$$\mathrm{H}_{\mathrm{SG}} = \begin{bmatrix} h_{77} & h_{78} & h_{79} \\ h_{87} & h_{88} & h_{89} \\ h_{97} & h_{98} & h_{99} \end{bmatrix}.$$

is the MIMO channel between HAP and users (static/mobile), the MIMO channel between HAP and Satellite(LMS/GEO) and the MIMO channel between Satellite and Ground Station respectively. We have assumed three users in the cell, each equipped with one antenna. The HAP also consists of three antennas well separated to avoid any correlation between MIMO channels and the satellite and ground station with three antennas each. As it is evident from the **Fig. 6.** and from the number of antennas we have used, increase in the number of users can introduce correlation among antenna elements. This can also happen if the users are not well separated geographically. A virtual channel model is not possible here as we have only one HAP available.

5) Integrated Terrestrial/HAPs/Satellites System

The progress of systems and services towards 4G and B4G wireless communications is to provide flawless delivery of broadband multimedia applications over mixed networks. While HAPs have many returns over terrestrial and satellite networks, the amalgamation of accessible and emerging HAPs technologies with terrestrial and satellite networks is imperative for lucrative long-term business. The equivalent system architecture that is used and essential for the integrated terrestrial/HAPs/satellites system is shown in **Fig. 7.** The MIMO channel model for this typical scenario can be easily deduced from scenario 3 mentioned in previous sections. The model is presented below,

$$\mathrm{H} = [\mathrm{H}_{\mathrm{HU}} \quad \mathrm{H}_{\mathrm{HB}} \quad \mathrm{H}_{\mathrm{HG}} \quad \mathrm{H}_{\mathrm{UB}} \quad \mathrm{H}_{\mathrm{SG}}],$$

where additional we have the channel matrix,

$$\mathrm{H}_{\mathrm{SG}} = \begin{bmatrix} h_{77} & h_{78} & h_{79} \\ h_{87} & h_{88} & h_{89} \\ h_{97} & h_{98} & h_{99} \end{bmatrix},$$

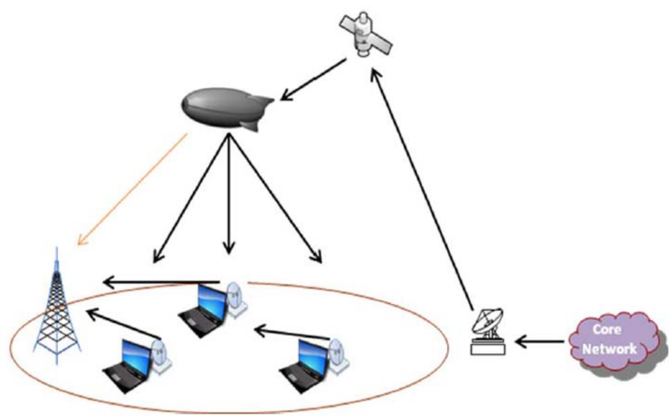

Fig. 7. Integrated terrestrial/HAPs/satellites system for global connectivity.

6) Multilayer Approach for Integrated Scenarios.

In [16], a layered system and services model has been anticipated and is shown in **Fig. 8**. This complete architecture consists of comprises five layers for provision of different services: global satellites including HAPs, global cellular communications, global wireless local area network (WLAN), global wireless personal area network (WPAN), and global broadband personal area network (B-PAN). Every layer of the system design is based on diverse hardware and software levels and different frequency ranges to giving services and other features by communicating among various layers and inside each layer. In addition to giving services to new areas, the space segment of the architecture in incorporated scenario can be used for providing of multimedia applications, localization and navigation services, internet, and communications in disaster relief scenarios. The user terminals design and condition of both uplink and downlink services depend upon commercial and technological tradeoffs [16]. The uplink and downlink services provided to user terminals can be given by means of HAPs or uplink services by means of HAPs and downlink services directly by satellites. Channel modeling for multi-layer method can become very multifaceted depending upon the number of layers of satellite used. If we only consider the HAP layer and a single GEO satellite then the MIMO channel model would be same as described in previous scenarios 2, 3 and 5 combined. As evident from the **Fig. 8**., various links can be formed between entities of the entire network. These are namely,

a) Inter-satellite link at GEO layer
b) Inter-satellite link at MEO layer
c) Inter-satellite link at LEO layer
d) Inter-HAP link at HAP layer
e) Cross-layer links between Satellite layers
f) Cross-layer links between Satellite and HAP layer
g) Mulithop communication between Satellite layer and HAP layer

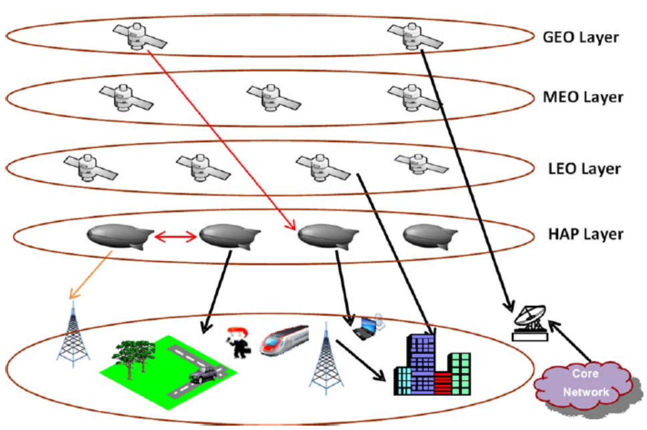

Fig. 8. Multilayer approach for integrated scenarios

Depending on the application various channel models can be constructed and discussed. We consider the case in which we have 2 GEO (Geostationary Earth Orbit) satellites, 3 MEO (Medium Earth Orbit) satellites, 4 LEO (Low Earth Orbit) satellites and 4 HAP's at the HAP layer for communication with the terrestrial network. We also assume here that the satellites and HAPs are all equipped with at least two antenna elements to communicate with satellites at own layer and with lower layers. The results can be generalized to more antennas very easily. We consider uplink data arriving from core network and through the ground station linked to the GEO satellite. From this GEO satellite responsible for global coverage sends the data to the users at the ground through various layers of networks. Now we consider Inter-satellite link at GEO layer. If there is a direct link between inter-satellite link and users then a Virtual MIMO would be constructed here. One of the satellites at the GEO layer is assigned to communicate with the lower layer of MEO satellites rendering the MIMO model to be a simple Single-Input Single Output (SISO) link. Now for the one GEO satellite to communicate with the MEO satellite network a SISO model would be assumed as one link would be established. This procedure follows for the rest of the layers as well namely for LEO layer and the HAP layer. The inter GEO link is given by,

$$H_{interGEO} = \begin{bmatrix} h_{11} & h_{12} \end{bmatrix},$$

assuming here 2 antennas for a single GEO satellite which is communicating with the other GEO satellite and with the satellite in the MEO layer. The GEO and MEO V-MIMO link is given by,

$$H_{GEO/MEO} = \begin{bmatrix} h_{33} & h_{34} \\ h_{43} & h_{44} \end{bmatrix},$$

The remaining MIMO channels are as follows,

$$H_{interMEO} = \begin{bmatrix} h_{55} & h_{56} \\ h_{65} & h_{66} \end{bmatrix}, \; H_{MEO/LEO} = \begin{bmatrix} h_{77} & h_{78} \\ h_{87} & h_{88} \end{bmatrix},$$

$$H_{interLEO} = \begin{bmatrix} h_{\{9\}\{9\}} & h_{\{9\}\{10\}} & h_{\{9\}\{11\}} \\ h_{\{10\}\{9\}} & h_{\{10\}\{10\}} & h_{\{10\}\{11\}} \\ h_{\{11\}\{9\}} & h_{\{11\}\{10\}} & h_{\{11\}\{11\}} \end{bmatrix},$$

$$H_{LEO/HAP} = \begin{bmatrix} h_{\{12\}\{12\}} & h_{\{12\}\{13\}} \\ h_{\{13\}\{12\}} & h_{\{13\}\{13\}} \end{bmatrix},$$

$$H_{interHAP} = \begin{bmatrix} h_{\{14\}\{14\}} & h_{\{14\}\{15\}} & h_{\{14\}\{16\}} \\ h_{\{15\}\{14\}} & h_{\{15\}\{15\}} & h_{\{15\}\{16\}} \\ h_{\{16\}\{14\}} & h_{\{16\}\{15\}} & h_{\{16\}\{16\}} \end{bmatrix},$$

The combined representation for downlink would then becomes,

$$H=\begin{bmatrix} H_{interGEO} & H_{GEO/MEO} & H_{interMEO} & H_{MEO/LEO} & H_{interLEO} & H_{LEO/HAP} & H_{interHAP} \end{bmatrix}$$

We observe from the channel matrices above that model entities become complex as satellites or HAP grow in numbers and also available antennas on each platform.

III. Conclusion

In this work we identified the potential applications and use of integrated three tier network of Satellite, HAP and terrestrial networks. Moreover we identified different variants of the network and significant usage. For each type of networks we analyzed the effects of various channel parameters namely XPD, number of antennas and number of entities used in the network to model the associated MIMO channel. We also discussed the impact of delay and synchronization by varying the system parameters. We conclude from our work that the arrangement of such networks depends heavily on the type of application, coverage area and delay requirements. Moreover we also conclude that although applying multilayer approach can help global coverage but the underlying MIMO channel model increases the complexity and synchronization issues, for both uplink and downlink channel models.

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REFERENCES

[1] D. Gesbert, M. Shafi, Dashan Shiu, P.J Smith and A. Naguib, "*From Theory to Practice: An Overview of MIMO Space time Coded Wireless Systems*", IEEE Journal of Selected Areas in Communications., 2003, Vol. 21, No. 3, pp. 281–302.

[2] G. J. Foschini and M. J. Gans, "*Layered Space-Time Architecture for Wireless Communication in a Fading Environment when Using Multiple Antennas*", Bell Labs Systems Technology Journal, 1996, Vol. 1, No. 2, pp. 41–59.

[3] L. Zheng and D. Tse, "*Diversity and Multiplexing: A Fundamental Tradeoff in Multiple Antenna Channels*", IEEE Transaction in Information Theory, 2003, Vol. 49, No. 5, pp. 1073–1096.

[4] G. M. Djuknic, J. Freidenfelds and Y. Okunev, "*Establishing Wireless Communications Services via High-Altitude Aeronautical Platforms: A Concept Whose Time Has Come?*" IEEE Communications Magazine, September 1997, pp. 128–135.

[5] T. C. Tozer and D. Grace, "*High-Altitude Platforms for Wireless Communications*", IEE Electronic Communications Engineering Journal, June 2001, pp. 127–137.

[6] D. Grace, N. E. Daly,T. C.Tozer, A. G. Burr and D.A.J.Pearce, "*Providing Multimedia Communications from High Altitude Platforms*", International Journal of Satellite Communications, November 2001, No. 19, pp. 559–580.

[7] T. Celcer, T. Javornik, M. Mohorcic and G. Kandus, "*Virtual Multiple Input Multiple Output in Multiple High-Altitude Platform Constellations*", IET Communications, 2009, Vol. 3, No. 11, pp. 1704–1715.

[8] P. Horvath, G. K. Karagiannidis, P.-R. King, S. Stavrou and I. Frigyes, "*Investigations in Satellite MIMO Channel Modeling: Accent on Polarization*", EURASIP Journal of Wireless Communications and Networking, 2007, Vol. 2007.

[9] "*AeroVironment launches Global Observer Program for the US Special OperationsCommand*",www.defenseupdate. com/newscast/0907/news/260907_hale_av.htm, 26 September 2007.

[10] NASA Pathfinder Plus Platform, www.dfrc.nasa.gov/gallery/photo/Pathfinder-Plus/index.html, January 2008.

[11] Lockheed Martin High Altitude Airship, www.globalsecurity.org/intell/systems/haa.htm, January 2008.

[12]Lockheed Martin HAA Program, www.lockheedmartin.com/products/HighAltitudeAirship/index.html, 2008.

[13] M. Mohorcic, D. Grace, G. Kandus, and T. Tozer, "*Broadband communications from aerial platform networks*", in Proc. 13th IST Mobile Wireless Communications Summit, Lyon, France, Jun. 27–30, 2004, pp. 257–261.

[14] U. Drcic, G. Kandus, M. Mohorcic, and T. Javornik, "*Interplatform link requirements in the network of high altitude platforms*", in Proc. 19th AIAA International Communication Satellite Systems Conference, Toulouse, France, Apr. 17–20, 2001, pp. 1–9.

[15] J.-J. Huang, W.-T. Wang, and H.-W. Ferng, "*Uplink capacity enhancement for an integrated HAPS-terrestrial CDMA system*", IEEE Communication Letters, vol. 11, no. 1, pp. 10–12, Jan. 2007.

[16] C. Loo, "*A statistical model for a land mobile satellite link*", IEEE Transactions on Vehicular Technology, 34 (3) (1985) 122_127.

[17] F. Fontan, M. Vazquez-Castro, C. Cabado, J. Garcia, E. Kubista, "*Statistical modeling of the LMS channel*", IEEE Transactions on Vehicular Technology, 50 (6) (2001) 1549_1567.

[18] Coldrey, M., "*Modeling and Capacity of Polarized MIMO Channels*", Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE , vol., no., pp.440,444, 11-14 May 2008

Aamir Habib (M'96) became a Member (M) of IEEE in 1996. He was born in Rawalpindi, Pakistan in October 1973. He received his BSc. Electrical Engineering from UET, Peshawar in 1996. From 2003-2005 he completed his Masters in Mobile and Satellite Communications from the University of Surrey, UK. He then pursued for another masters in Computer Engineering from UET Taxila, Pakistan in 2006. He earned his PhD. degree from Vienna University of Technology in June 2012 in Electrical Engineering

He main area of research is in the field of Mobile and Satellite communications. His work include the area of MIMO and specifically antenna subset selection for future wireless communication systems . He has published in a number of high impact factor journals and international reputed conferences. He is also a permanent reviewer for IEEE transactions and vehicular technology conferences.

Qamar-ul-Islam completed his B Sc. Engineering, Electrical/ Telecomm (1982): University of Engineering and Technology, Lahore, Pakistan. He then completed - M Sc. Satellite Communications Engineering (1986): University of Surrey, England. He then did his Ph.D. (1991): University of Surrey, England.

He is and international expert in the area of satellite systems and wireless communication. Has more than twenty years of international experience in research, development and teaching in Pakistan, England, Saudi Arabia, and North America. Presently, Head of Department (HoD), Communication Systems Engineering at the Institute of Space Technology, Islamabad (2005 to date). Responsible for all departmental activities, including undergraduate, graduate and research work.