Multi-hop Relay in Next Generation Wireless Broadband Access Networks: An Overview

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Abstract. Relay technologies have the potential to offer extended cell coverage and improved capacity over the Next Generation Wireless Broadband Radio Access Networks. Standards development organizations are considering how to incorporate relay technologies into new standards. This article provides an overview of the relay-based technology concepts for two of the most promising next generation wireless broadband networks: WiMAX and LTE, focusing on some of the most pertinent aspects. In particular, the various potential relaying scenarios are described, while the integration and adaptation of the Multi-hop Relay in the framework of WiMAX and LTE networks is analyzed. Some consideration of the issues in designing such systems is also given, which highlights when different features within the standard are most appropriate. As these systems are very new, many open issues remain to be resolved.

Keywords: Next Generation Wireless Broadband Access Networks, WiMAX, LTE, Multi-hop Relay technologies, Relay Station.

1 Introduction

The rapidly growing demand for affordable bandwidth in fixed and mobile services is driving the telecommunications and advanced technologies industries to deliver high performing, cost effective wireless broadband platforms that can be deployed in the varied spectral allocations worldwide [1]. These platforms, addressing the bandwidth demands, share key technology enablers including Orthogonal Frequency Division Multiplexing (OFDM) air interface, advanced antenna techniques including Multiple-Input-Multiple-Output (MIMO) and beamforming, flat all IP architectures, etc [2].

The major next generation wireless broadband access platform candidates are Worldwide Interoperability for Microwave Access (WiMAX) and Long Term Evolution (LTE). These two platforms meet the needs for fixed, nomadic and mobile communications, including voice, data, video, gaming and personal broadband, in enterprise, residential, underserved, campus, special events, wholesale and safety & security applications [2]. In order for WiMAX and LTE to deliver ubiquitous broadband content,

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the network is required to provide excellent coverage both outdoor and indoor and significantly higher bandwidth per subscriber. The wireless Multi-hop Relay Station technologies currently receive much interest as they intend to fulfill these challenges [3]. The major benefit of these techniques leads to the fact that a Relay Station does not require any dedicated backhaul equipment as it receives its capacity from centralized base stations via the same resources used for the access service.

The rest of the paper is organized as follows: A brief overview on WiMAX and LTE standards is given first. Multi-hop relay networks basic concepts and how they are adopted in WiMAX and LTE platforms is then presented. Finally, the most common multi-hop relay scenarios are described.

2 WiMAX and LTE Standards Overview

2.1 WiMAX (802.16e and Beyond)

WiMAX technology evolution initially started with the IEEE802.16d [4]. Next step was NWG 802.16e Release 1.0 [5], [6], defined by Network Working Group (NWG) of WiMAX Forum. Release 1.5, which provides backwards compatible with Release 1.0 is expected in 2010. Finally, WiMAX Forum expects to specify 802.16m like the future WiMAX technology in order to get the 4G challenges. 802.16m provides higher data rates, reduced latency and efficient security mechanism. The availability of this release is expected in 2012. Mobile WiMAX air interface characteristics are summarized in Table 1.

Table 1. Mobile WiMAX Air Interface characteristics

Characteristic	Description
Channel Bandwidth	5, 7, 8.75 and 10 MHz
DL multiple access	OFDMA
UL multiple access	OFDMA
Duplexing	Time Division Duplexing (TDD)
Subcarrier mapping	Localized and distributed
Subcarrier hopping	Yes
Data modulation	QPSK, 16QAM and 64QAM
Subcarrier spacing	10.94 KHz
FFT size (5 MHz)	512
Channel coding	Convolutional coding and convolutional turbo coding
MIMO	Beamforming, Space-time coding and spatial multiplexing

In terms of network features, WiMAX Forum NWG [6], [7] defines a reference architecture for the WiMAX network interconnection with other networks, which is independent of the radio interfaces. A set of reference points has been specified, including interfaces, protocols and procedures. Fig. 1 represents a logical-functional architecture of the WiMAX network. A set of functional entities and reference points are identified. The entities are described as follows: *SS/MS (Subscriber Station/Mobile Station)* providing network connectivity to the user, *ASN (Access Service Network)* providing radio connectivity to the users and *CSN (Connectivity Service Network)* providing IP connectivity.

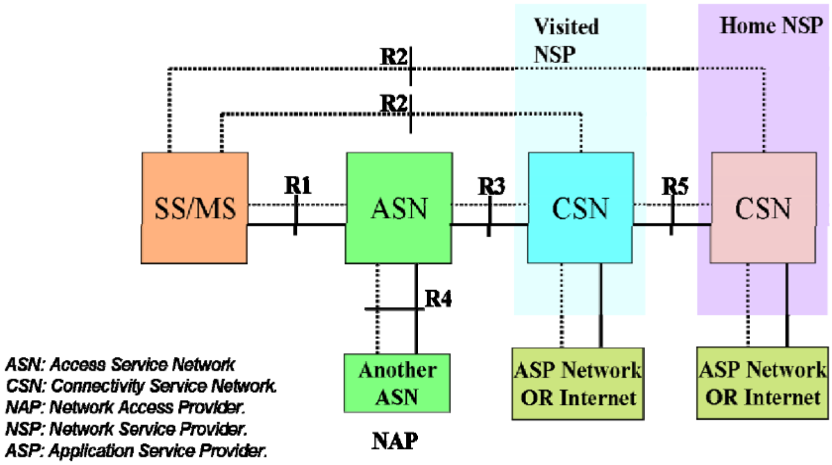


Fig. 1. Reference Architecture of the WiMAX Network

2.2 LTE and LTE-Advanced

LTE [8] is the project within 3GPP designed to improve UMTS standard to cope with future technology evolutions. LTE defines a high-speed radio access method for mobile communication systems and offers a path for operators deploying 3GPP and non-3GPP technologies to higher speeds and lower latency [9]. 3GPP standard evolution started with release 99 that specified UMTS/WCDMA technology. Next step was HSDPA and HSUPA technologies specified in Release 5 and 6 respectively. Release 7 specified HSPA+, the link between HSPA and LTE. Today, LTE specifications are encapsulated in Release 8, which was finalized and approved in January 2008 and it is target deployment in 2010. 3GPP has also started to work in the next evolutionary broadband systems, called LTE-Advanced. Table 2 summarizes LTE air interface characteristics.

Table 2. LTE Air Interface characteristics

Characteristic	Description
Channel Bandwidth	1.4, 3, 5, 10, 15 and 20 MHz
DL multiple access	OFDMA
UL multiple access	SC-FDMA
Duplexing	FDD and TDD
Subcarrier mapping	Localized
Subcarrier hopping	Yes
Data modulation	QPSK, 16QAM and 64QAM
Subcarrier spacing	15 KHz
FFT size (5 MHz)	512
Channel coding	Convolutional coding and turbo coding
MIMO	Multi-layer precoded spatial multiplexing space-time/ frequency block coding, switched transmit and cyclic delay diversity

In terms of network features, LTE supports flat all-IP network architecture allowing interworking with legacy 3G networks and high mobility between heterogeneous access networks. In addition, LTE is expected to substantially improve end-user throughput, sector capacity and reduce user plane latency [10]. To achieve these challenges, the global LTE network architecture is composed of: *Evolved UMTS Terrestrial Radio Access Network (E-UTRAN)* been composed of eNodeB (eNB) elements and *Evolved Packet Core (EPC) architecture* supporting E-UTRAN through the reduction in the number of network elements.

From a high level point of view, LTE architecture consists of the following functional elements: *eNodeB (eNB)* which is the base station in LTE access network and is in charge of all radio interface-related functions, *Mobility Management Entity (MME:* which is in charge of managing mobility, *Serving Gateway (S-GW)* which routes and forwards user data packets and *Packet Data Network Gateway (PDN-GW)* which provides connectivity to the UE to external packet data networks.

Fig. 2 illustrates the high level architecture for LTE and the interconnection between all the functional elements [10].

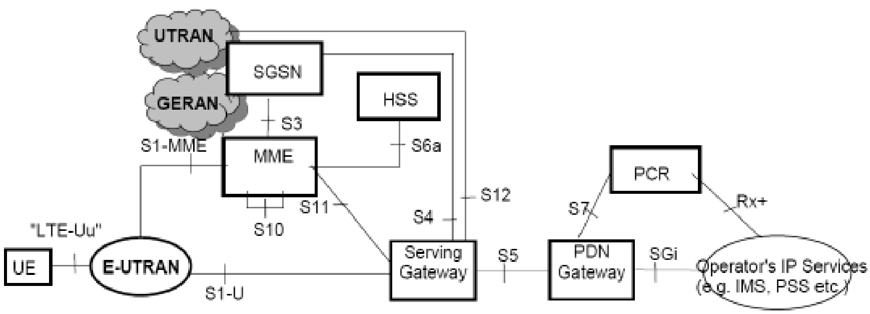


Fig. 2. LTE Network Architecture

3 Multi-hop Relay Networks

The current backhaul network architectures are based primarily on leased lines. This is inadequate for offering future broadband services. Moreover, coverage improvement and capacity enhancement are always the essential requirements for wireless broadband networks in order to deliver cost-effective wireless services. Due to the higher demand for high quality multimedia applications, capacity enhancement is a must for the next generation cellular networks. Furthermore, as the data rate demand of mobile applications increases, the effective coverage range given a fixed transmit power becomes less.

Initially, this problem has been addressed by deploying stations in a denser manner. However, the high manufacturing, deployment and maintenance cost render this approach less desirable. Multi-hop relay technology was created to deal with these issues. It is a cost-effective deployment because relay stations do not need wired backbones. The technique of augmenting cellular networks with multi-hop relay networks has been applied to different types of wireless network with the main objectives of enhancing cellular coverage, increasing system throughput, helping overcome obstacles, balancing load within wireless access networks, providing flexible wireless network access and finally helping decrease the cost since they are much cheaper than base stations.

Nowadays, multi-hop relay networks have become promising wireless networking architecture for future wireless access system and relay technology is being standardized by different forums and organizations. Relays are being standardized in WiMAX technology through the IEEE 802.16j working group, which enhances multi-hop relay defined in IEEE802.16e. 3GPP organization is also working on relay technology (3GPP named stations “repeater”), based on communication relaying protocol proposed for UMTS TDD mode to be applied in LTE technology.

3.1 Multi-hop Relay in WiMAX Networks

There are various choices available for WiMAX networks operators to improve indoor or outdoor coverage or to increase network capacity. These choices include different types of base stations: macrocells, microcells, or picocells in an outdoor environment, picocells in public indoor locations or within enterprise buildings, and femtocells for residential. The primary difference between them is the size of coverage. Macrocells have the longest range, but are also the most expensive to purchase, deploy and maintain. Micro, pico and femto base stations are used to fill in coverage gaps and establish coverage in buildings where the macrocell signals can hardly penetrate. A significant side-effect of placing a large number of base stations in a region is that each needs a dedicated broadband backhaul connection. Micro, pico, and femto cells can use wireless links for their backhaul. In particular, they can support in-band backhaul to enable operators to use their spectrum holdings to carry backhaul traffic to the nearest macro base station.

IEEE 802.16j working group is responsible for generating a standard for WiMAX Mobile Multi-hop Relay (MMR) network. A set of technical issues are specified in order to enhance previous standards (IEEE 802.16e) with relay support.

Multi-hop Relay Station (RS) provides additional coverage or performance advantage in an access network. In RS networks, the Multi-hop Relay BS (MR-BS) is connected to several Relay Stations (RSs), in a multi-hop topology, in order to enhance the network coverage and capacity density. Traffic and signaling between the Mobile Subscribers (SS) and MR-BS are relayed by the RS thereby extending the coverage

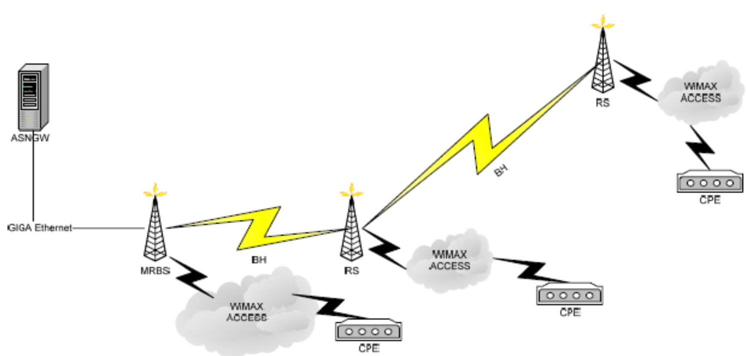


Fig. 3. A two-hop Relay Station deployment example

and performance of the system in areas where RSs are deployed. Each RS is under the supervision of an MR-BS. In a system with more than two hops, traffic and signaling between an access RS and MR-BS may also be relayed through intermediate RSs. The RS is fixed in location. The MS may also communicate directly with the MR-BS. Fig. 3 illustrates the MR-BS and two-hop RS deployment. For each of the RS there is an ACCESS link that covers the current cell and a BACKHAUL link to the next cell.

The interconnection between these nodes includes the following link classification:

Table 3. Relay 802.16j links

Links	Description
MR-BS to MS	The MR-BS can associate with multiple MSs
RS to MS	The RS can associate with multiple MSs
MR-BS to RS	The MR-BS can associate with multiple RSs

The main technical issues being discussed in the IEEE 802.16j work group are new frame structure to support Relay Stations, centralized vs. distributed control, centralized vs. distributed scheduling, radio resource management, power control, call admission and traffic shaping policies, QoS based on network wide load balancing and congestion control, security and management.

Focused on NWG reference architecture, Fig. 4 identifies the reference points and the functional entities in which relay technology should be included. A new ASN entity, called ASN-Relay, is focused on relay concepts. This entity will establish all relay network functionality defining a new reference points called R1', which consists of the protocols and procedures to establish the communication links defined above. Moreover, it will be compatible with R1 and R6 reference points, because RSs and MRBS must be compliant with IEEE802.16e standards.

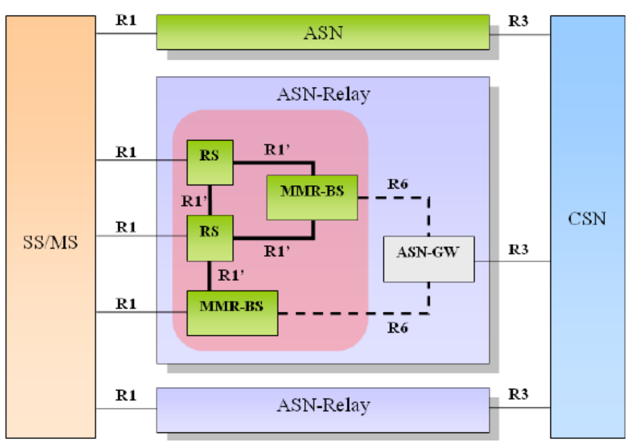


Fig. 4. Relay Technology Proposal in NGW Reference Architecture

3.2 Multi-hop Relay in LTE Networks

LTE, which promises real data rates up to 100 Mbps and by using MIMO antennas it can reach few hundred of Mbps, is almost complete. Consequently, the usage of relay stations in LTE networks appears to be inevitable. LTE Advanced, which will include relay stations, is in process of being standardized by the 3GPP for Release 10. However, there are many issues regarding the introduction of relay stations in LTE networks that must be taken into consideration. Among them the most important are the frame structure to be used due to the existence of relay stations, the transmission power control algorithm, a method to overcome interferences among random access signals and backward compatibility. There is a continuously increasing demand for high spectral efficiency for a certain geographical area that will be satisfied by the use of multi-hop relay stations in an LTE network. But there is also a demand of smaller cell sizes in order to achieve the previous. If this should be implemented only with conventional base stations (eNBs) it would result in high cost for eNB deployment and operation. Therefore, small eNB cells can be replaced by relay 'cells' at reduced backhaul cost.

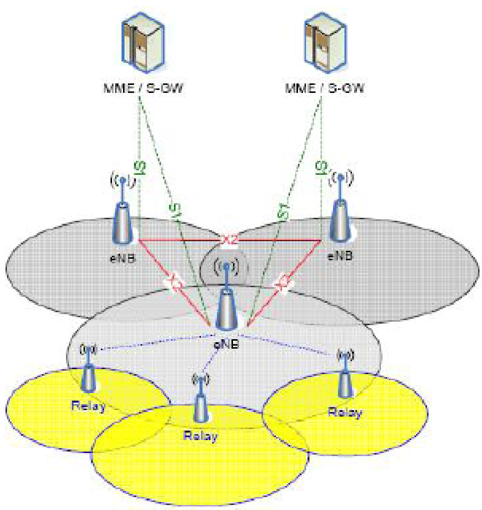


Fig. 5. Relay Technology Proposal in NGW Reference Architecture

3GPP has considered two deployment scenarios of relay nodes. The first scenario considers that the coverage of the cell is provided by an LTE eNodeB. The serving eNodeB supports direct connections to and from LTE-Advanced UE and legacy LTE UEs while a relay station may be deployed in the cell for providing additional coverage at cell-edge or coverage holes to all UEs that are located in these areas. UEs communicate with the serving eNodeB in uplink and downlink direction through the intermediate relay station(s). The other scenario includes a legacy LTE eNodeB serving the area. The requirements are the same as in the first scenario with the only difference that legacy NodeB is obliged to be capable of connecting to relay station.

Relay stations can be transparent and non-transparent. Transparent relays mean that UE is not aware of whether it communicates or not with the network via relay. Transparent relay has certain advantages in the sense that it will introduce no impact to the UE so it could be used to improve the coverage and cell-edge throughput for LTE Advanced and Release 8 system. On the other hand, if a relay station is going to be deployed to support LTE advanced UEs as a non-transparent relay, it could be used to function as transparent relay for certain Release 8 UEs. In this case, no additional deployment cost will be needed.

4 Multi-hop Relay Scenarios

A RS can be adapted at several mobility levels, i.e. fixed, nomadic, mobile, and can be used in the Next Generation Networks for improving the communication quality by several aspects, depending on the user needs and the environment conditions and constraints. In this section, the most common relay scenarios are described.

4.1 Hole Filler

A RS can be used inside the service area of the cell in order to improve link quality to those specific areas that do not have sufficient link quality due to excessive link attenuation from the BS. This attenuation can be caused among other factors due to shadowing of buildings or due to a given hilly topography. Such a scenario is shown in Fig. 6.

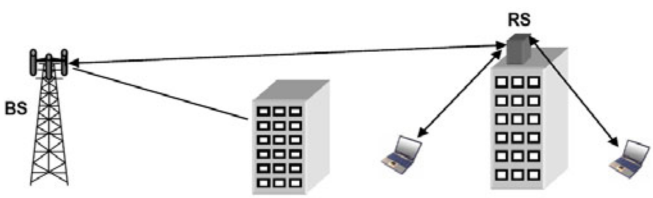


Fig. 6. Hole Filler Relay Station Scenario

4.2 Cell Extension

In this case, a RS is used to increase the coverage area of a cell. A RS can extend the coverage area in a certain location at the edge of the cell as shown in Fig. 7a or cover an area separated from the coverage area of the cell as shown in Fig. 7b. This latter configuration is sometimes called "remote sector". Cell extension can be used in a more strategic manner where multiple RSs are deployed around the perimeter of a cell to achieve higher coverage area with a single BS, as shown in Fig. 7c. This concept may be used as a part of the network design strategy in order to provide coverage with as few as possible base stations.

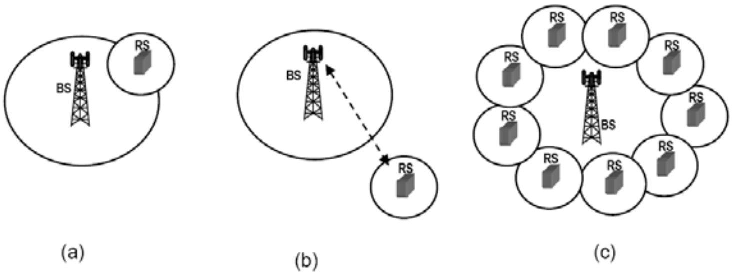


Fig. 7. Cell Extension Relay Station Scenario

4.3 Capacity and Throughput

In most scenarios, the use of an RS can increase the per-MS throughput, system capacity and QoS. A single link between the BS and RS with high Signal to Interference plus Noise Ratio (SINR) (and as a result with high order modulation and coding scheme) can be replaced with multiple RS to BS links with low SINR. The result is an increase in spectral efficiency which produces a capacity increase. This additional capacity can be used for providing higher throughput to individual MSs or to support more MSs within the coverage area of the RS. In addition, the link reliability is enhanced due to improved SINR.

Fig. 8 depicts a scenario where four RSs are deployed in the service area of a sector. The capacity of the original coverage area may increase by a factor of four due to the fact that each RS provides its own capacity to the area and MSs which had low quality link to the BS may have better link quality to the serving RS. This increase in link quality is translated by the inherent link adaptation process to higher throughput and therefore to a higher capacity.

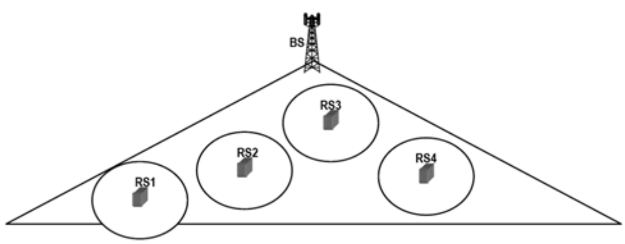


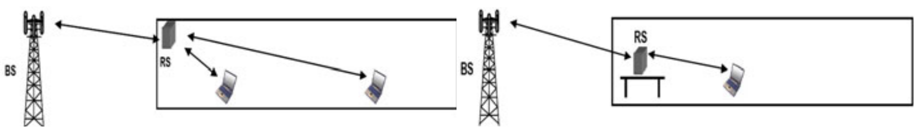
Fig. 8. Capacity and Throughput Improvement Relay Station Scenario

4.4 Indoor Usage Scenarios

The majority of cellular traffic is generated from buildings. Providing service to indoor MSs by the same BS that provides service to outdoor MSs has several major disadvantages. First, due to the building walls introduced attenuation, BS-MS link might be marginal or of a low quality thus limiting the data rate and consuming excessive time-frequency resource from the BS. MSs which reside in high floors of a building, pose another issue. They are exposed to multiple BSs arriving signals and as a result, two problems may occur: First, signals may interfere with each other, hence degrading the SINR of the MS. Second, MS may enter into an undesired hand off process and as a result, excessive handover processes might occur. This may result in power consumption of the radio, backhaul and computational resources.

Relaying technologies in indoor environments can be proved challenging in order to improve the communication. The major methods used for providing dedicated coverage for indoor MSs are described below.

Fixed and Nomadic RS with direct connection to the BS. A fixed RS is mounted in a way that its antenna maintains good link quality concurrently with the BS and with the MSs which reside in the building. Alternatively, the RS may be lightweight, nomadic, similar to a WiFi router.



(a) (b)

Fig. 9. A Relay Station with direct connection to the Base Station in an indoor scenario. In (a) the Relay Station is Fixed, while in (b) the Relay Station is Nomadic.

Multi-hop RS. When large area floors need to be covered, a single RS may not be sufficient. In such cases, multiple RSs can be distributed over the floor connected to each other using the multi-hop capability. The internal RSs can be chained to a RS mounted at the edge of the floor with a good link to the BS as depicted in Fig. 10.

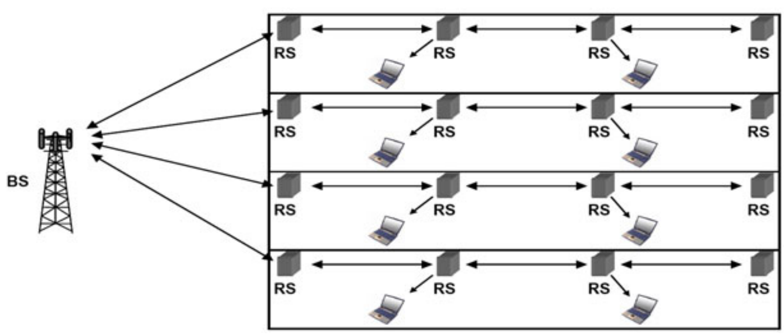


Fig. 10. A Multi-hop Relay Station indoor scenario

Coverage with dedicated external RSs. In some cases it may possible to provide in-building coverage with external RSs "illuminating" the building from outside as depicted in Fig. 11. The advantage of this model is the elimination of the excruciating need for installing equipment and cabling inside the building.

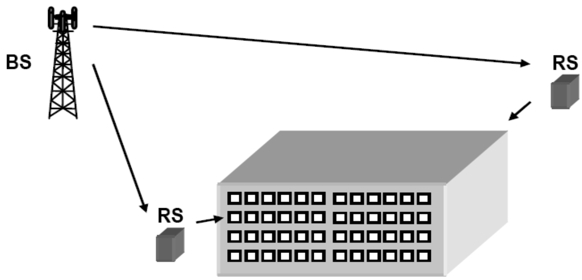


Fig. 11. Two external Relay Stations illuminating a building

4.5 Road and Tunnel

The common requirement for roads and tunnels is the need to provide coverage along a linear path. Since high mobility MSs are served, it is recommended to allow the move without handover between the coverage area of each RS. Fig. 12 depicts a scenario where a BS feeds in parallel three transparent RSs. This configuration allows continues high SINR connection along the road without handover.

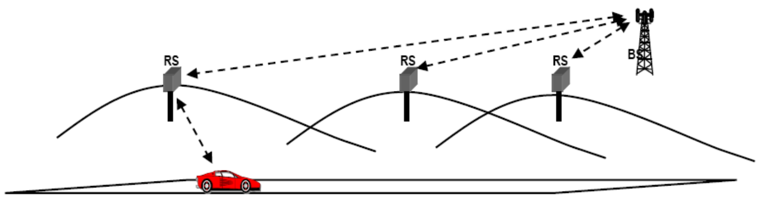


Fig. 12. A Base Station feeds three Relay Stations in parallel

Fig. 13 shows a tunnel covered by RSs. The RSs inside the tunnel have no connection with the external BSs and therefore multi-hop RSs must be used. In order to minimize the number of hops, the internal RSs can be split to two groups each fed from a BS at each side of the tunnel.

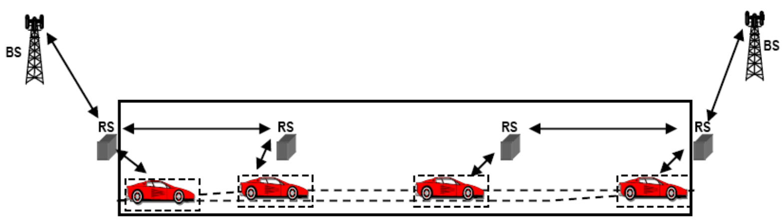


Fig. 13. A tunnel coverage through a multi-hop Relay Station configuration

4.6 Temporary Relay Stations

RSs may be deployed temporarily to provide coverage or additional capacity. An example would be in events where a heavy load on the network is expected only in certain predefined time interval such as sporting events, concerts or other events where a large crowd is expected to gather. In the case of adding capacity to an area where an event takes place, usually reasonable coverage from the macro BS already exist. In another usage model a relay can be used for providing coverage in areas where network coverage is needed temporarily for an incidental reason. An example would be an emergency incident or a disaster recovery effort where fixed infrastructure network has been destroyed overloaded or never existed before. Service to that cases can be provided by a deployment of temporary RS usually suitably installed on a vehicle.

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