Switched-Beam Antennas For Stratospheric Platform Mobile Communications

Yasser Albagory
Faculty of Electronic Eng.
Menouf, Egypt

Mostafa Nofal
Faculty of Electronic Eng.
Menouf, Egypt

Moawad Dessouky
Faculty of Electronic Eng.
Menouf, Egypt

Mohiy Hadhood
Faculty of Electronic Eng.
Menouf, Egypt

Abstract - **In this paper, we suggest several switched-beam smart antenna techniques in order to increase the user location accuracy especially in emergency situations, reduce power consumption, efficiently use the radio spectrum and reduce the errors resulting from the positional instability of the platform. In addition, the performance and feasibility of such approaches in terms of the hardware and processing requirements are addressed. The study dictates the adoption of beam-splitting approach as a superior one due to its compromise between the hardware and processing requirements.**

I. INTRODUCTION

The development of newly developing regions requires an extension of the telecommunications infrastructure to provide service to such areas. The major limiting factors are the system cost and deployment flexibility as well as startup time. Examples for such developed areas in Egypt are Toshky, North Sinai, Red sea coast, and Northern coast regions. In these regions a wide coverage is needed with low cost infrastructure. Users may exist at any location within these regions and this dictates continuous user tracking. Deploying terrestrial communication systems will be inefficient in terms of the system cost and wide coverage provision. While adapting the counterpart, satellite systems may provide wide area coverage. This approach may lead to extremely and unaccepted high cost. One of the recently mobile radio communications is the stratospheric platform communication system [1,2,3,4]. The platform is an airborne body that can be stationary at an altitude of about 20 km. At such altitude, the wind velocity is minimum and therefore results in reducing the shift in position due to the wind forces and allows easier ground control. The radio coverage can be established by several methods. These include using highly directive antennas or an antenna array with beamforming networks to form the cells on the ground surface. The design flexibility of the system allows changing the platform location or its coverage beams according to the traffic loads. This is an important capability especially during the startup phase. The major points that must be considered in the platform operation are the capability of the system to track the user (a feature in the emergency situations), the power saving (as the solar and fuel cells are the main power sources for the platform operation) and the suitable beamforming system to satisfy the proper radio coverage. In the current paper, we investigate different approaches for providing the radio coverage of the platform. There are many schemes to satisfy this requirement; for example using the smart antenna technology will add more benefits to the system [5,6]. In this technique, the user can be tracked by narrow beams that provides gain to the received and the transmitted signals and results in more power saving. There is a capability to reuse the same radio channel within the same cell leading to efficient use of the radio spectrum. The received signal from a mobile of a user communicating with the platform at such altitudes comes with a narrow angular spread and can be considered as a point source. Therefore using narrow beams can provide information about the user location. This information is very useful especially in emergency situations. The smart antennas include the adaptive and switched-beam systems. The later provides lesser complexity in application than the former. Therefore we emphasize in this paper on the application of the switched-beam antenna system that is more suitable for covering large area cells. The existing mobile communications systems utilize the digital technology in transmission and based on frames each consisting of several time slots used for data or voice transmission. The inclusion of a training sequence in each traffic channel can be used for user verification and identification [7]. This is to distinguish between the desired and interfering signals. The application of the switched beam antenna system can be achieved in two phases. The first is the user acquisition by a searching procedure over the entire covered area. So it is advantageous to utilize such unique user codeword in the acquisition step and the subsequent switching process. The second step is the actual beam switching operation as the user moves toward a new area covered by another beam. The switching operation can be also done if the channel service quality degrades and there is another beam that have a better channel quality even if it is not in its covered area.

The paper is organized as follows. Section II discusses the general block diagram of the switched beam system. Section III introduces several schemes that can be applied. The performance and comparison between such techniques are summarized in Section IV and finally some concluding remarks are introduced in Section V.

II. THE BASIC SWITCHED-BEAM SYSTEM

A general block diagram of a switched-beam antenna system is shown in Fig. 1. The system consists of the following:

- A number of antenna elements that are used either as an array or high gain spot beam antennas.
- A beamforming network responsible for the formation of the narrow beams for user tracking and usage.
- User verification block for each formed beam to perform user acquisition and verification. This block consists of a matched filter that's designed for the user training sequence, a squaring block for power measurement and an averaging process for reducing the error in beam selection.
- A selection block: the outputs of the user verification blocks are used to decide the proper beam selection. The output of this block is a control signal that is used in the beam-switching matrix.
- Beam-switching matrix: a set of switches that are connected to the beamformer outputs. The output of such block is the final user signal.

As noted, the switched-beam antenna system may have several schemes depending on the beamforming process employed in forming the narrow beams. In the following, we are going to discuss such schemes.

III. THE PROPOSED SWITCHED-BEAM TECHNIQUES

The formation of narrow beams to provide radio coverage can be achieved by several approaches such as high-gain spot-beam antennas, a two-dimensional-phased array, a scanning narrow beam antenna array, and splitting a wide coverage beam into a number of narrow beams. Each method is characterized by its own processing time and hardware complexity. We introduce a thorough discussion of such techniques emphasizing on the feasibility for application to the existing systems.

1- The Multiple-Spot Beam Antennas

This approach implies a direct implementation of multiple spot-beam antennas as in the terrestrial systems. The number of antenna elements equals that of the required narrow beams (user beams), consequently the block of the beamforming network displayed in Fig.1 is no longer needed. Furthermore, the number of the user-verification branches equals the number of antenna elements. Each antenna element may be a parabolic dish type or the beams can be formed by multiple feed reflector antenna. In order to search for a user in the coverage area, we need to monitor all the beams covering the whole area. Although the processing time is minimum as the beams are processed in parallel or at the same time, a larger hardware is required. The beamwidth of each antenna is unfortunately fixed and cannot be changed. The need for changing the beamwidth of the user beam originates when there is a multiple switching operation due to multipath signals arising from objects around the user as this results in a frequent and erroneous beam switching. Consider an area that can be covered by M beams and the needed time for user verification is T seconds, also the averaging is done over K verification cycles, so the needed processing time for beam selection will be KT seconds. The needed user verification branches or blocks as shown in Fig. 1 is M and if there are a maximum of U active users, the total needed verification or validation branches will be UM.

2- The Multiple-Beam Antenna Array

This technique is similar to the aforementioned one but the beams are formed using two-dimensional phased antenna array. The use of multiple antenna elements in forming the beams provides flexibility in tailoring the beamwidth needed for a specific operation. Controlling a set of weight vectors, each corresponds to a specific beam direction, forms the beams. As shown in Fig. 2, a two-dimensional antenna array lays in the x-y plane with a number of elements in the x and y directions of M_x and N_y respectively. The interelement separations are d_x and d_y for the same directions, respectively. This array of elements is attached to a beamforming network consisting of a set of weights forming the weight vector as shown in Fig. 3. This weight vector is responsible for the formation of the narrow beam. The weight vector needed to form a beam in a specific direction is chosen to be equal to the steering vector at that direction, which is known as conventional beamforming. Therefore the beamforming network of Fig.1 consists of such weight vectors. For the planar arrays, the steering vector is given by [8,9]:

$$S(\theta,\phi)=\begin{pmatrix} 1 & e^{j\left(\frac{2\pi}{\lambda}d_x\,sin\theta cos\phi\right)} .. e^{j\left(\frac{2\pi}{\lambda}d_y\,sin\theta sin\phi\right)} .. e^{j\left(2\pi d_{l,k}\,sin\theta cos\phi_{l,k}\right)} ...... e^{j\left(2\pi d_{Mx,Ny}\,sin\theta cos\phi_{Mx,Ny}\right)} \end{pmatrix}^T \quad (1)$$

where

$$d_{l,k} = \sqrt{\left((l-1)\frac{d_x}{\lambda}\right)^2 + \left((k-1)\frac{d_y}{\lambda}\right)^2} \tag{2}$$

and

$$\phi_{l,k} = \phi - tan^{-1}\left(\frac{(k-1)\ d_y}{(l-1)\ d_x}\right) \tag{3}$$

where λ is the wavelength, (θ,ϕ) is the main lobe direction, and l ,k are the element order in the x and y-directions respectively. The total received signal at this element, $x_{l,k}(t)$, is composed of the induced signal $u_{l,k}(t)$ plus a background noise $n_{l,k}(t)$ and is represented as

$$x_{l,k}(t) = u_{l,k}(t) + n_{l,k}(t) \tag{4}$$

The output of the beamformer is given by

$$y(t) = \sum_{m=1}^{M_x}\sum_{n=1}^{N_y} w_{m,n}^{*} x_{m,n}(t) \tag{5}$$

where $w_{m,n}$ is the weight value and $w_{m,n}^{*}$ is its complex conjugate. Equation (6) can be rewritten in a matrix notation as

$$y(t) = W^H X(t) \tag{6}$$

where

$$W = \left(\ w_{1,1}\ w_{1,2}\ \ldots w_{1,N_y}\ , w_{2,1}\ w_{2,2} \ldots w_{2,N_y}\ , \ldots.. w_{M_x,N_y}\ \right)^T \tag{7}$$

with *T* and *H* refers to the transpose and complex transpose of *W*. In order to get a beam in a certain direction (θ_o,ϕ_o), the weight vector of the beamformer is made equal to the steering vector at that direction or

$$W = S(\theta_o,\phi_o) \tag{8}$$

For a square array (i.e. with M_x = N_x = N and $d_x = d_y = \lambda/2$), the beamwidths BW_θ, BW_ϕ (defined in Fig. 4) of such formed beam are given by [10,11]

$$BW_\theta = sec\,\theta_o\ \theta_d \tag{9}$$

$$BW_\phi = \theta_d \tag{10}$$

where θ_d is the beamwidth of a one-dimensional array of *N* elements

$$\theta_d = sin^{-1}\left(sin\,\theta_o + \frac{0.886}{N}\right) - sin^{-1}\left(sin\,\theta_o - \frac{0.886}{N}\right) \tag{11}$$

where BW_θ, BW_ϕ are defined in Fig. 4. The variations of the beamwidths as a function of the number of elements at different directions are shown in Figs. 5 and 6. As depicted in these figures, the beamwidth decreases as the number of elements increases but increases as the elevation angle decreases. This is because for lower elevation angles, the effective aperture of the array decreases so the directivity decreases and hence the beamwidth increases. In this approach, the number of beams formed may be less than the number of antenna elements leading to more hardware than the previous method. In general, For a maximum of *U* active users, and an *M* beams covering the whole area, the required weight vectors are *M* and the number of validation branches is *UM*. The processing time needed is the same as the previous method (i.e. *KT*).

3- The Single Scanning Beam

This approach adopts a single beam that scans the coverage area for user search. Changing the weight vector in a discrete manner either by switching between predetermined steering vectors or changing the coefficients of a single weight vector by preset values can achieve this. The hardware requires a steering processor in order to control the scanning operation and sequence. So, if we use a single changing weight vector as shown in Fig. 7, the needed hardware is minimum, but on the other hand the processing time is maximum. In each beam scan, the user is checked by the validation subsystem and the result is stored in memory for averaging with other beam scans results. Over several scan cycles these results are averaged and used for the beam selection. Therefore the processing time for the beam selection will be multiples of *KT*. The longer processing time may be not desirable especially in the fast fading environments. The process although requires minimal hardware, it seems to be very difficult to apply in scanning a large coverage area accommodating a large number of narrow beams.

4- The Beam-Splitting Approach

A compromise between the hardware requirements and the processing time for user location acquisition may be possible by splitting a wider beam into a number of narrow beams. In each splitting phase, the narrow beams are checked in parallel and the appropriate beam is chosen for the subsequent examination. The operation is repeated until reaching to the narrowest beam. The idea is depicted in Fig. 8 where the coverage is layered and each layer is emerged from a specific splitting operation. This splitting operation is achieved by both controlling the number of antenna elements as well as the steering coefficients used in the forming each beam. The current approach provides more flexibility in the system operation. For example, consider the situation when the multipath signals arising from wide angular spread. This results in an erroneous beam selection and higher beam-switching rate. Therefore to mitigate this problem using this approach, the splitting operation may stop at a wider beam than the narrowest one thus reducing the higher switching rate and the possibility of erroneous beam selection. If the splitting is made with a ratio of 1:*S* and there are *M* beams that can cover the whole area, the needed number of splitting operations, *D*, will be

$$D = \frac{\log M}{\log S} \qquad (12)$$

In addition, the number of processed beams will be *DS* while the required time for beam selection will be multiples of *DSKT* seconds. For example if the splitting ratio is made to be 1:3, and the total number of beams, *M*, to cover the service area is 81 beams, then the number of splitting steps will be 4. On the other hand, the needed validation branches will be *US* rather than *UM* branches as in the first and second approaches. The system requires a steering processor for controlling the steering coefficients in order to determine the direction and beamwidth of each beam as shown in Fig. 8. A problem may arise with this approach when the user moves to an area that corresponds to another splitted beam as shown in Fig. 9. In this case the checking operation is done upwardly with wider beams. After selection of the satisfied beam, the splitting operation is performed. This may require a temporary channel until reaching to the narrow beam for user. This is because a wider beam may result in an increase in the carrier-to-interference ratio with the other co-channel beams.

The approaches discussed earlier are used for user acquisition mode. The subsequent operation is simply the traditional beam-switching one. In general, a wide beam for control and user acquisition covers the service area. The user, once enters this served area, is sensed by this beam. If he gets an incoming call or attempts to place a call, the acquisition mode is checked in order to assign a radio channel to that user through the service narrow beam.

IV. PERFORMNCE MEASURES AND COMPARISON

The use of switched-beam technology in the stratospheric platform communications provides some improvements in the system operation. One of the major benefits is the power saving due to focusing on the user location by narrow beams that provide a gain to the received and transmitted signals. Because of the limited nature of the power sources onboard the platform, this power saving is very beneficial. Furthermore, using narrow beams instead of the wider ones allows the system to track the user movement efficiently with an improved accuracy. Assuming that the service area can be covered by *M* beams instead of a single beam, the user location accuracy is *M* folded. This depends on the fact that a user at such distance with the platform is considered as a point source with a narrow angular spread received signal at the platform, which is similar to the satellite channel. At some emergency situations such as fires or snatch, this location information will be very important in providing the rescue. Another important issue is the capability of reusing the same radio channels within the same cell. This is because the number of users of such regions is not large at the system initiate, but expected to increase with time. Therefore the reuse of the radio spectrum for such systems will improve the spectrum efficiency. The platform as an airborne body will endue some instability in position due to the wind forces exerted on. This instability will affect the radio coverage because the beams will move also if the platform rotates for example. The switched-beam system will overcome this difficulty especially when the ground control is temporarily lost. The proposed approaches for the platform communication system are compared in table 1. The performance measures for comparison are the hardware required and the needed processing issues. In this table the needed time for user validation is assumed to be *T*, the averaging cycles are *K*, the number of beams covering the area under consideration is *M*, the maximum number of users the system can attain is *U*, the splitting ratio is *S* and the number of splitting levels is *D*.

Table 1

COMPARISON FACTOR	SPOT-BEAM ANTENNAS	MULTIPLE-BEAM ANTENNA ARRAY	SINGLE-SCANNING BEAM	BEAM-SPLITTING
Number of Validation Branches	*UM*	*UM*	*U*	*US*
Steering Processor	Not Needed	Not Needed	Needed	Needed
Number of Processed Beams / User For Acquisition	*M*	*M*	*M*	*SD*
Processing Time Required for Beam Selection	*KT*	*KT*	Multiples of *MKT*	Multiples of *DSKT*

V. CONCLUSION

The recently emerging technology of stratospheric platform mobile communications is devised for covering the newly developed regions, where the cost of deployment is the main limiting factor for radio coverage extension. Providing radio service with the terrestrial or satellite counterparts suffers from the higher cost and/or limited flexibility. The new developed regions have a smaller user density and it is possible for those users to exist at any location within the covered area, dictating an efficient coverage scheme. Applying the smart antenna technology with the platform communications may provide many benefits and flexibility in operation. The major advantages are the saving in power consumption, the capability of user tracking and location determination, efficient use of the radio spectrum, and the compensation for the positional instability of the platform due to the wind forces. As an application to the smart antenna, we emphasize on the use of switched-beam technology and introduce several proposed schemes. A performance and feasibility discussion for these proposed methods were investigated in terms of the hardware and processing requirements. The comparison dictates the adoption of the beam-splitting approach as a superior technique in terms of both hardware and processing time requirements.

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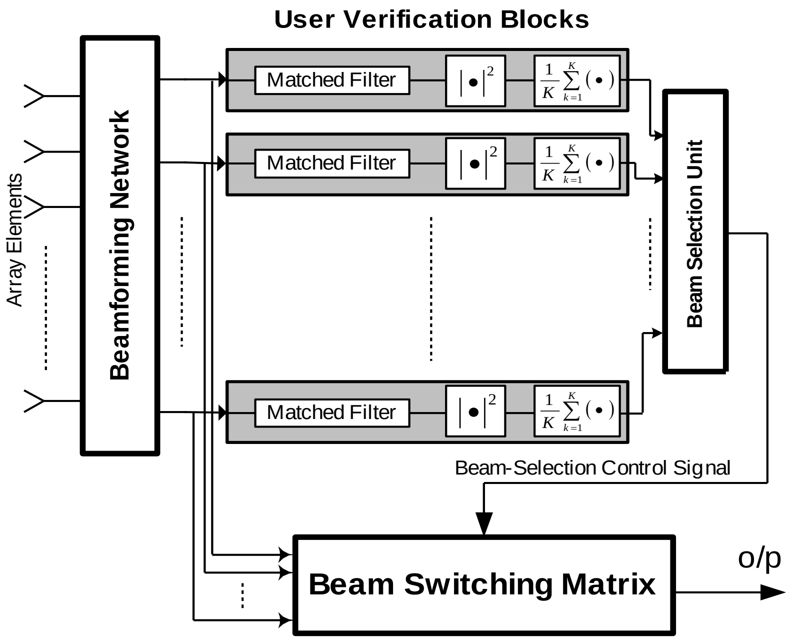

Fig. 1. General switched-beam system

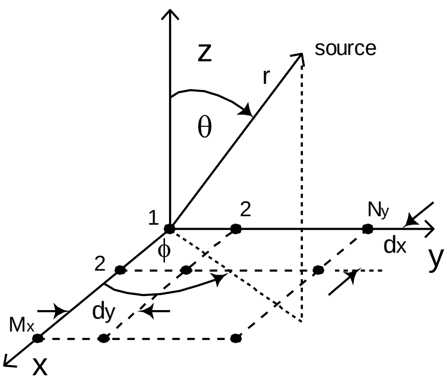

Fig. 2 Two-dimensional antenna array

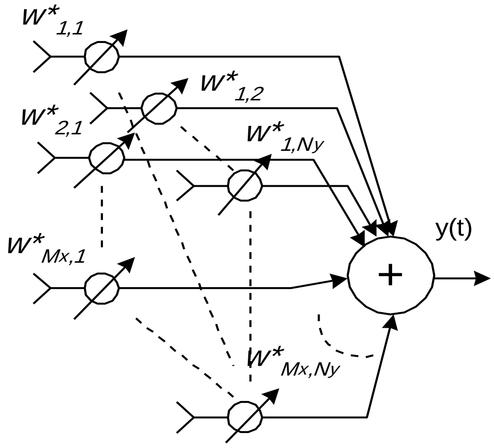

Fig. 3 Two-dimensional antenna array beamformer

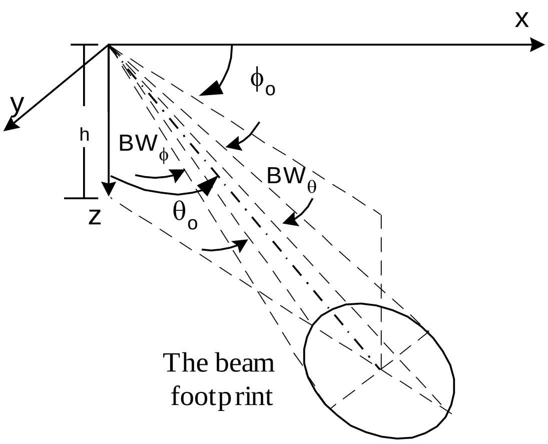

Fig. 4 The beam footprint and beamwidths

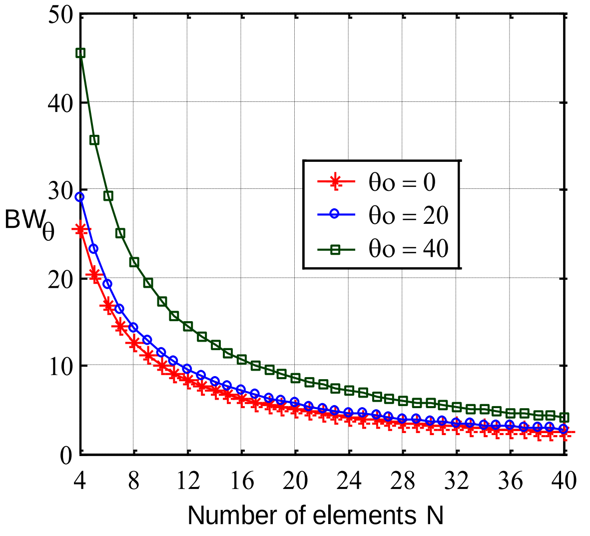

Fig. 5 BW_{θ} in degrees versus number of elements (N) at different beam orientation angle θ_o

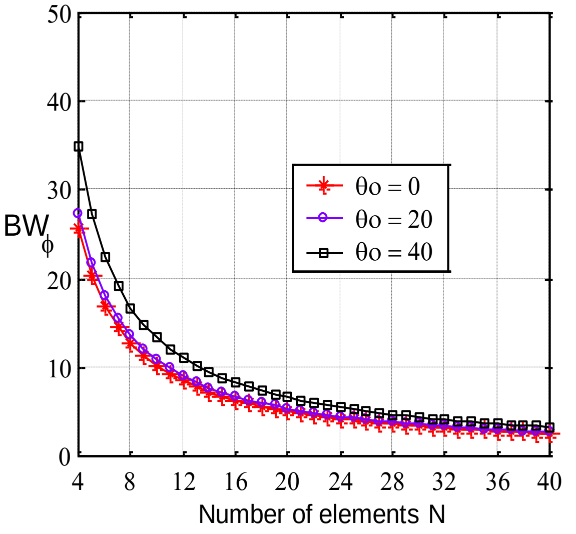

Fig. 6 BW_{ϕ} in degrees versus number of elements (N) at different beam orientation angle θ_o

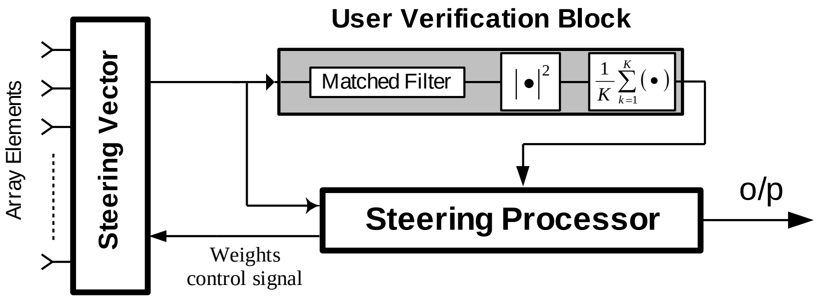

Fig. 7 The block diagram of the single-scanning beam switching system

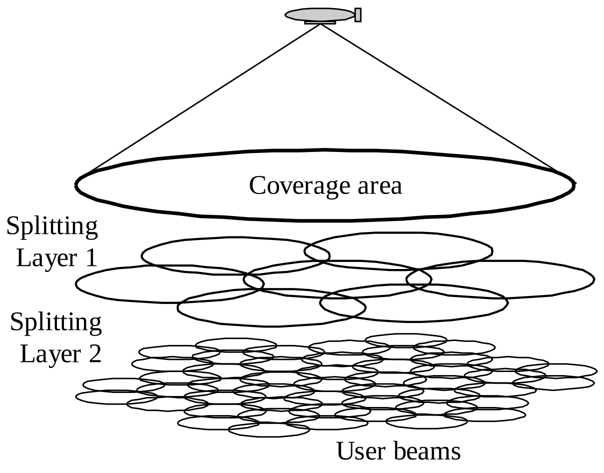

Fig. 8 Beam-splitting for user acquisition

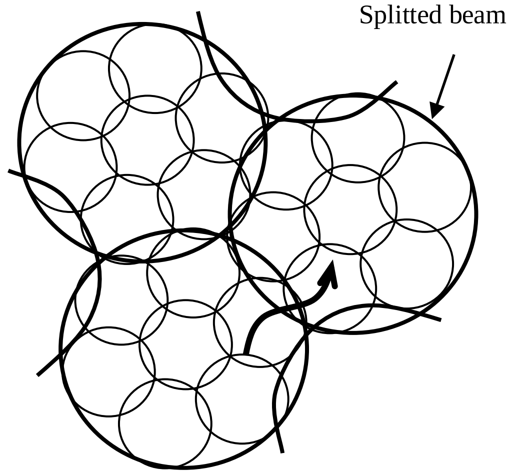

Fig. 9 A user moving toward an area covered by higher layer coverage beam