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An overview of multi-antenna technologies for space-ground integrated networks

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Abstract Multi-antenna technologies have already achieved a series of great successes in the development of information networks. For future space-ground integrated networks (SGINs), the traditional various kinds of separated information networks will converge to a whole fully connected information network to provide more flexible and reliable services on a world scale. Regarding their great successes in existing systems, multi-antenna technologies will be of critical importance for the realization of SGINs and multi-antenna technologies are definitely one of the most important enabling technologies for future converged SGINs. In this article, a comprehensive overview on multi-antenna technologies is given. We first investigate multi-antenna technologies from a theoretical viewpoint. It is shown that we can understand multi-antenna technologies in a general and unified point of view. This fact has two-fold meanings. First, the research on multi-antennas can help us understand the relationships between different technologies e.g., OFDMA, CDMA, etc. On the other hand, multi-antenna technologies are easy to integrate into various information systems. Following that, we discuss in depth the potentials and challenges of the multi-antenna technologies on different platforms and in different applications case by case. More specifically, we investigate spaceborne multi-antenna technologies, airborne multi-antenna technologies, shipborne multi-antenna technologies, etc. Moreover, the combinations of multi-antenna technologies with other advanced wireless technologies e.g., physical layer network coding, cooperative communication, etc., are also elaborated.

Keywords MIMO, multi-antenna technologies, signal processing, space-ground integrated networks, satellite networks, terrestrial networks

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1 Introduction

Applications of multi-antenna technologies in information systems already have a very long history [1], but its evolvement never stops [2]. It is a genius idea to exploit multi-antenna arrays to control spatial resources. In this way, an extra dimension has been revealed in available resources and thus an additional degree of freedom is introduced into information networks [3]. Different from time and frequency,

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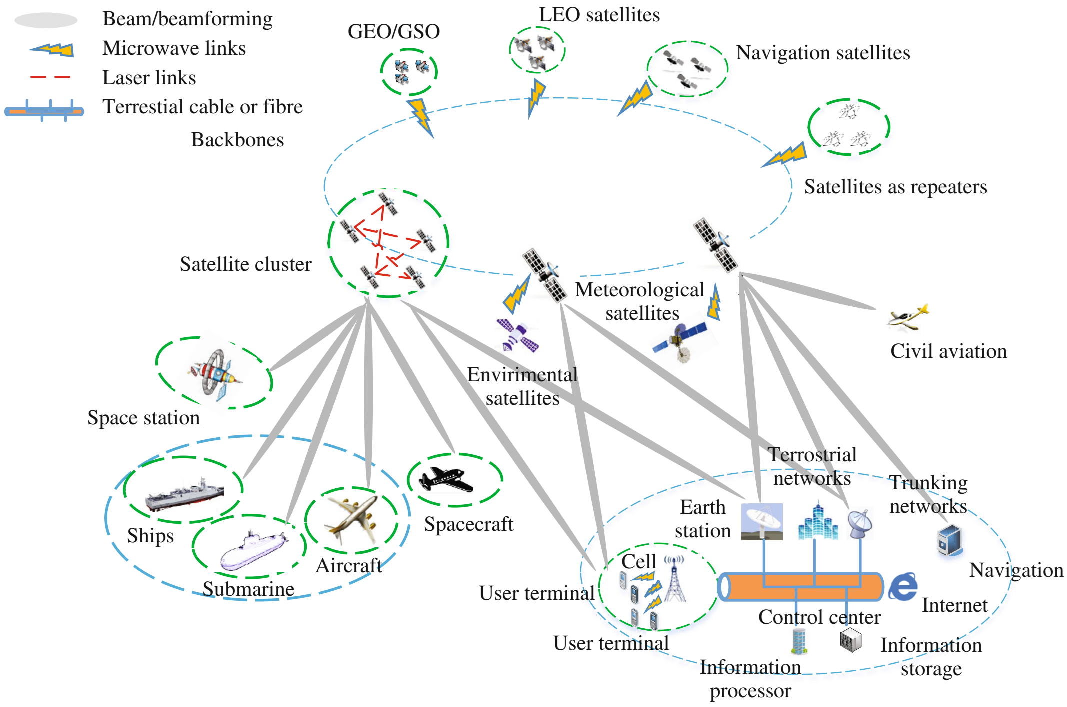

Figure 1 (Color online) Space-ground integrated networks (SGINs).

spatial resources are easy to be manually controlled. Neglecting space limitations, more antennas usually mean more spatial resources that can be exploited. Multi-antenna technologies have a wide of applications including information transmission, localization, signal detection, radar imagining, etc. In future information networks, multi-antenna technologies will play a more and more important role.

Generally speaking, for information systems, diversity and multiplexing are unity of opposites, which always exist. Unsurprisingly, for spatial resources, there are also spatial diversity and multiplexing gains. If we only focus on spatial diversity gains, the most representative technology is array signal processing technologies which take advantage of antenna arrays to realize spatial filtering and then to improve system performance [2]. On the other hand, when both spatial diversity and multiplexing gains are considered, the multi-antenna system becomes to be a more general multiple-input multiple-output (MIMO) system. It is undoubted that MIMO is a milestone in the development of multi-antenna technologies. MIMO is the name of a glorious era in the development of communication theory and information theory. Up to date, its flame even does not faint.

For terrestrial communications, MIMO technologies have been widely standardized, e.g., IEEE 802.20, 802.22, 802.11n, 802.16e, 802.16m, and so on. For four generation (4G) communication networks, MIMO is one of the most important enabling technologies to realize high data rates and high frequency efficiency. Furthermore, for fifth generation (5G) communications, much higher power efficiency and spectrum efficiency are expected [4, 5]. For example, for 5G 1000 times higher data rate per-area is required and meanwhile the communication delay should be smaller than 1ms [6]. These challenges on physical layer entail scaling up MIMO [7, 8]. An evolved version of MIMO namely massive MIMO or large scale MIMO has attracted a lot of attention [9].

The great success of multi-antenna technologies in terrestrial cellular networks results in the plethora of the applications of multi-antenna technologies in various information networks. Antenna arrays can be deployed on various kinds of information terminals to effectively mitigate interferences and improve communication quality. Nowadays, it is widely accepted for engineers that an effective way to mitigate interference and enhance received signal quality at destinations is to deploy antenna arrays. Specifically, airplanes, satellites, ships and vehicles all can be equipped with multiple antennas to improve information transmission rates or signal detection accuracy.

Accompanying the globalization of human activities satellite communications become to be an important and fundamental communication technology to realize reliable connections anytime and anywhere. Generally speaking, satellite communications have distinctly different characteristics when compared to terrestrial communications [10] because of its service coverage, transmission delay, link geometry, channel impairments, special interference and so on [11, 12]. Engineers and researchers expect the great successes of MIMO technologies can also be grafted onto satellite communications. This is really an ambitious goal. Strictly speaking, the availability of MIMO technologies is determined by the instinct channel characteristics of the considered satellite communications [10, 13–17]. It is because different kinds of satellites have different orbits, different operating frequencies, different applications, and so on. These facts will significantly affect the signal correlations among the antenna arrays [18]. If the signal orthogonality is destroyed, the spatial multiplexing gain of a MIMO channel will decrease or even disappear [19]. Moreover, the resources on satellites are more limited than their terrestrial counterparts. For example, it is very costly or even impossible to repair antenna arrays on a working satellite. Moreover, the payload and physical size of a satellite are very limited as well. However motivated by thirsty demands for high quality communications the applications of MIMO for satellites are proliferous recently [20–27].

Nowadays, information networks become to be more and more heterogeneous in order to support the connections for different information terminals [28–30]. In order to meet the ever increasing service demands, information networks should be able to support various applications that can be foreseen or not. In addition, information networks should be flexible enough, robust enough, reliable enough, and even cheap enough. To realize global communication services, especially information exchanges between any two terminals, connection (the most fundamental network functionality) becomes to be a new problem for future network designs regarding the existing largely different networks and the corresponding quite different network interfaces. In future, converged satellite and terrestrial networks become to be a versatile network candidate for future information sharing. This kind of networks is named as space-ground integrated networks (SGINs) which can realize reliable connections among a large variety of information terminals as shown in Figure 1. Recently, the related topics for SGINs have attracted lots of attention from wireless researchers [31]. Most existing literature work focuses on the challenges in network architectures of SGINs, however the physical layer of SGINs cannot be neglected, which supports the network layer. To realize high quality connections between different information terminals in SGINs, multi-antenna technologies will definitely have a much wider range of applications. To the best of the authors' knowledge, the research on multi-antenna technologies in different networks are almost separately implemented and up to date a comprehensive overview is still missing. This is the motivation of this work.

In this paper, a comprehensive discussion on multi-antenna technologies for SGINs is provided. At the beginning, the theoretical fundamentals of multi-antenna technologies are reviewed. It reveals that MIMO is not only a technology that bring performance improvement but also can give us some interesting and indepth understanding on some complicated and fancy technologies. Following that both the potentials and challenges of multi-antenna technologies in different applications and on different platforms are investigated case by case. It is shown that on different platforms multi-antenna technologies always have important applications that can support the important services of SGINs. These discussions demonstrate that multi-antenna technologies are an important and necessary enabling pillar for future SGINs.

2 Fundamentals of multi-antenna technologies

In this paper, for simplicity in the following discussions, multi-antenna technologies and MIMO technologies are not distinguished with each other as MIMO systems are more general than multiple-input single-output (MISO) systems or single-input multiple-output (SIMO) systems. Although a typical MIMO system is built by deploying multiple antennas at source and destination nodes, its theoretical framework can cover a series of other technologies as its special cases, e.g., Code Division Multiple Access (CDMA), Orthogonal Frequency Division Multiplexing (OFDM), and so on [32]. This is because MIMO is a general linear system and many systems are in nature linear systems. Specifically, for a point-to-point MIMO system the signal model can be written in the following form [32]

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{w}, \tag{1}$$

where $\boldsymbol{r}$ is the received signal at destination. The matrix $\boldsymbol{H}$ is the MIMO channel matrix between source and destination. Its row number is the receive antenna number and its column number is the transmit antenna number. The vector $\boldsymbol{x}$ denotes the signal vector transmitted from source. The noise vector $\boldsymbol{w}$ is usually Gaussian distributed. The signal model in (1) can be understood as a general linear system corrupted by additive noises. Just as previously discussed, many systems can be transferred into (1).

In this following, the signal model of OFDM is taken as example to illustrate this fact. Denoting $\boldsymbol{s}$ as the transmitted signal in the time domain, the signal in the frequency domain is $\boldsymbol{F}\boldsymbol{s}$ where $\boldsymbol{F}$ is a discrete Fourier transform (DFT) matrix. The received signal in time domain at the destination is

$$\boldsymbol{y} = \boldsymbol{F}^{\mathrm{H}}\boldsymbol{\Lambda}\boldsymbol{F}\boldsymbol{s} + \boldsymbol{n}, \tag{2}$$

where the ith diagonal element of the diagonal matrix $\boldsymbol{\Lambda}$ is the channel fading parameter on the ith subcarrier. Finally, the vector $\boldsymbol{n}$ is the additive noise in the domain at the destination. It is obvious that if taking $\boldsymbol{F}^{\mathrm{H}}\boldsymbol{\Lambda}\boldsymbol{F}$ as an equivalent channel matrix $\boldsymbol{H}$, the OFDM signal model becomes to a special case of the MIMO signal model. We would like to highlight here that however the signals have the same mathematical formulas, this does not mean these two systems are the same. From an implementation viewpoint, hardware requirements for OFDM and MIMO systems are totally different. It is because MIMO channel consists of a series of spatial channels between different antenna elements while OFDM channel consists of different frequency bins. This example shows that from theoretical perspective MIMO model is very fundamental and the research is of critical importance for information networks.

2.1 MIMO channel models

Based on the above MIMO signal model, it can be concluded that channel characteristics significantly affect system performance. Generally speaking, in full scattering environments such as indoor or urban environments, MIMO channels will be full rank [33]. In other cases, the correlations between adjacent antennas should be carefully considered as the correlations will destroy spatial orthogonality. With regard to correlations, the widely used channel MIMO model is Kronecker model of the following form [2]

$$\boldsymbol{H} = \boldsymbol{\Sigma}^{1/2}\boldsymbol{H}_W\boldsymbol{\Psi}^{1/2}, \tag{3}$$

where $\boldsymbol{\Sigma}$ is the receive correlation matrix and $\boldsymbol{\Psi}$ is the transmit correlation matrix. Each element of the matrix $\boldsymbol{H}_W$ is an i.i.d. Gaussian distributed random variable with zero mean and unit variance. In most existing work, the MIMO channel row and column correlations are modeled as exponential correlations.

In order to make the availability of the transmission for multiple spatial data streams, there are usually some requirements on the spacing between adjacent antennas. Roughly speaking, the distance between adjacent antennas should be larger than half wavelength in order to make sure there are no serious correlations. There are several different ways to overcome the space limitations on MIMO antenna arrays,. For example, if the communication systems work at high frequency bands, antenna elements can be manufactured in much smaller sizes. Additionally, cross polarization can be also exploited to realize signal orthogonality between adjacent antennas [13, 15, 34]. Moreover, multiple terminals can cooperate to act as virtual MIMO, such as satellite clusters [31]. This idea can be considered as an extension of the concept of cooperative multiple points (CoMP) [35].

2.2 MIMO optimization

2.2.1 *MIMO training optimization*

To fully realize the great potential performance gains promised by MIMO technologies, channel state information (CSI) is usually required at both source and destination otherwise blind algorithms are needed, which usually incur slow convergence rate and high computational complexity. As a result, a basic task for MIMO systems is to estimate channel parameters. In the channel estimation procedure, training sequences are transmitted from source to destination. After that at destination the channel matrix will be estimated from the received signals which are corrupted by additive noises. To estimate as accurately as possible, some estimator e.g., maximum likelihood (ML), linear minimum mean square error (LMMSE) or least squares (LS) can be used to estimate the channel parameters. Generally speaking, LS estimator does not require the statistical information, while LMMSE is implemented based on the channel second order statistics.

2.2.2 *MIMO transceiver optimization*

Linear transceiver: Linear MIMO transceivers are widely used due to its low complexity and satisfied performance. In the context of linear MIMO transceivers, linear precoding and linear equalizer are adopted at source and destination, respectively. There are various performance metrics for linear MIMO transceiver designs, e.g., capacity, MSE, BER, etc. This is because of the multi-objective optimization nature when there are multiple data streams simultaneously transmitted from source to destination. Different tradeoffs among the diagonal elements of MSE matrix will result in different transceiver designs. A natural choice to realize these tradeoffs is to use weighted MSE as the performance metric for the transceiver optimization problem. The most representative optimization problems are capacity maximization and sum MSE minimization. To unify various linear MIMO transceiver optimizations, the different performance metrics can be formulated as additively Schur-convex/concave functions of the diagonal elements of data detection MSE matrix [32].

Nonlinear transceiver: Referring to nonlinear transceiver designs, the most popular nonlinear transceivers are based on feedback structures at transmitter side and receiver side. At the receiver side, decision feedback equalizer (DFE) can be used to effectively detect signals. On the other hand, at the transmitter side, Tomlinson-Harashima precoding (THP) can be used. DFE and THP have an elegant duality between each other. Generally speaking, THP has a slightly better performance than DFE, because at transmitter side there is no error propagation effect. Similarly to linear transceiver optimization, based on majorization theory different performance metrics for nonlinear transceiver optimization can be formulated as multipplicatively Schur-convex/concave functions of the diagonal elements of the Cholesky decomposition matrix of data detection MSE matrix [36].

2.2.3 *The unified MIMO optimization*

Because of multi-antenna arrays, MIMO increases the dimensionality of the involved optimization problems. Roughly speaking, optimization variables are generalized from vectors to matrices. There exits a great difference. For example, vectors do not have determinant and inverse operations. It means that the increase in dimensionality changes the nature of the optimization problem. By the way, the research on MIMO systems permits us to use more compact and elegant MIMO algebras to analyze considered complicated information systems.

Based on MIMO signal models, the capacity and sum MSE formulas become [37]

$$\begin{aligned} \text{Capacity:} \quad & \log|\boldsymbol{I} + \boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P}|, \\ \text{Sum-MSE:} \quad & \mathrm{Tr}[(\boldsymbol{I} + \boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P})^{-1}], \end{aligned} \tag{4}$$

where $\boldsymbol{P}$ is the precoding matrix at source and $\boldsymbol{R}_n$ is the noise's covariance matrix. Compared to the traditional single antenna case, we can say that in MIMO systems, SNR becomes a Hermitian matrix $\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P}$. Properly recognizing this matrix version SNR can facilitate the analysis and system designs in complicated space-ground integrated networks. The eigenvalues of $\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P}$ correspond to the SNRs on different space eigenchannels. A specific eigenvalue decomposition (EVD) unitary matrix $\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P}$ corresponds to the realization strategies of transceiver optimizations. Therefore, the previously discussed various MIMO transceiver optimizations can be unified into a new optimization problem of the following form [36, 38]

$$\begin{aligned} \max_{\boldsymbol{P}} \quad & \boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{R}_n^{-1}\boldsymbol{H}\boldsymbol{P} \\ \text{s.t.} \quad & \mathrm{Tr}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}}) \leqslant P, \end{aligned} \tag{5}$$

where P is the maximum transmit power at the source node. This kind of optimization problem is named as matrix-monotonic optimization. Based on this optimization framework, the optimization problems can be discussed in a unified and comprehensive manner and it will be convenient to integrate MIMO technologies into space and terrestrial information networks e.g., [22, 26].

2.2.4 *Robust transceiver designs*

Strictly speaking, perfect CSI is only an ideal assumption because the training sequences have limited length and wireless channels are time varying. As a result, channel estimation errors are inevitable. Channel estimation errors may seriously reduce system performance. To mitigate the negative effects, robust transceiver designs are of critical importance and attracted lots of attention. The models of channel uncertainties determine the robust transceiver design philosophy. With regard to robust transceiver designs, there are generally three kinds of designs. The first one is min-max or worse case robust designs. For worse case designs, the robust design aims at guaranteeing the performance at the worse case in channel uncertainties. This kind of robust designs focuses on norm bounded channel errors. The second one is based on Bayesian philosophy. This kind of robust designs aims at optimizing the average performance over a randomly distributed uncertainty. The third one is outage based robust designs which make sure the probability that the QoS constraint is satisfied higher than a predefined threshold.

The importance of robust transceiver designs are two-fold. First, robust transceiver designs can reduce the negative effects of channel uncertainties (channel estimator errors or feedback errors) and the system performance are greatly improved. On the other hand, robust transceiver reveals the relationship between channel errors and system performance. It is worth noting that channel errors are functions of training sequences and thus the robust design can reveal complicated relations between transceiver optimization and training optimization. As a result, scarce wireless resources can be further optimized to achieve a better performance. For example, with channel estimation errors, MIMO channel can be written as follows

$$\boldsymbol{H} = \hat{\boldsymbol{H}} + \Delta\boldsymbol{H}_W\boldsymbol{\Phi}^{1/2}, \tag{6}$$

where $\hat{\boldsymbol{H}}$ is the estimated channel and the second term on the righthand side $\Delta\boldsymbol{H}_W\boldsymbol{\Phi}^{1/2}$ is channel estimation error. The correlation matrix $\boldsymbol{\Phi}$ is a function of channel statistics and training sequences. Based on this channel error model, the corresponding capacity maximization problem can be formulated as

$$\begin{aligned} \max_{\boldsymbol{P}} \quad & \log\left|\boldsymbol{I} + \frac{\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{P}}{\sigma_n^2 + \mathrm{Tr}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}}\boldsymbol{\Phi})}\right| \\ \text{s.t.} \quad & \mathrm{Tr}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}}) \leqslant P. \end{aligned} \tag{7}$$

Different form the optimizations with perfect CSI, the matrix version SNR is $\frac{\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{P}}{\sigma_n^2+\mathrm{Tr}(\boldsymbol{P}\boldsymbol{P}^{\mathrm{H}}\boldsymbol{\Phi})}$ instead of $\boldsymbol{P}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{P}/\sigma_n^2$ [36].

2.3 Massive MIMO

By installing a large scale antenna array, massive MIMO arrays can significantly improve communication quality and spectrum efficiency [39]. Recognizing that it is one of the most important enabling technologies for future 5G communications, the research on massive MIMO has gained lots of attention from both academia and industry.

In a massive MIMO system, the antenna array equipped at base station consists of a few hundred antennas. Serving a much smaller number of users, massive MIMO boosts communication capacity 10 times and meanwhile improves energy efficiency 100 times. Similar to traditional phased array antennas, massive MIMO technologies will also be applicable to space-ground integrated information networks.

With large numbers of antennas, wireless channels become hardening and thus massive MIMO can simplify the design of multiple access (MAC) lager. Traditional high complexity operations become much simpler. Linear transceivers tend to be optimal. The complicated matrix inversion can be implemented in a low complexity manner using series expansion. Massive MIMO can be realized by using inexpensive and low power antenna elements. Massive MIMO is able to significantly reduce the latency on the air interface of cellular networks. It is because massive MIMO can take advantage of the law of large numbers and beamforming to avoid deep fading. Using a large number of antennas, massive MIMO systems are more robust than the traditional MIMO systems. On the other hand, it is worth noting that there are also a series of challenges that will be faced with when massive MIMO is applied in practice. For example, the most famous challenge may be pilot contamination. Specifically, in a multi-cell scenario it is impossible to guarantee the pilots used by adjacent cells are strictly orthogonal with each other. In addition, in time-division duplexing calibration for channel reciprocity may need more overhead.

3 Characteristics of space-ground integrated networks

The concept of SGINs is not strictly limited to satellite networks and terrestrial networks. Actually, it includes a much wide range of networks. Rigorously speaking, SGIN is an X-integrated network that comprises all available networks. As a result, this kind of network is significantly different from terrestrial cellular networks [15, 34, 40–42]. In SGINs, different terminals have largely different velocities. For example, satellites, aircrafts, helicopters, and cars move at different speeds. According velocities, an SGIN can be divided into different levels of heterogeneous networks. For a given velocities, the terminals have the similar data rate requirements and the corresponding channel characteristics are similar as well. In each level, the network architecture has been well developed, while the communications across different levels should be carefully designed.

SGINs aim at providing connection over a much wider area. Heterogeneous network architecture makes network wide optimization and control to be very challenging. With largely different delays and Doppler offsets, a unified signal processing framework is far from desired. Simultaneously, considering some imperfect effects e.g., cloud attenuation, tropospheric scintillations and so on, the realization of the functionalities of SGINs becomes more difficult. To realize SGINs, the involved signal processing algorithms should be able to deal with different delays, different doppler effects and robust to unexpected interference [43].

For complicated networks, physical layer should be transparent to higher layers. Additionally, the involved physical layer technologies should be easy to integrate to build a whole network system. Multi-antenna arrays are deployed on different platforms. Then a detailed review on multi-antenna technologies is of great importance for future SGIN research. Integration also takes place in functionalities including transmission, sensing, navigation, detection and so on. Various functionalities can be realized on a unified hardware platform. Application oriented multi-antenna technologies and platform based multi-antenna technologies will be discussed in detail in the following sections.

3.1 Applications of SGIN

Generally speaking, SGINs have many important application scenarios. Due to space limitation, in the following, the authors only give three of the most representative scenarios.

3.1.1 *Communications in disaster areas*

In disasters SGINs are very important. For example, after earthquake or flood, the fundamental facilities of terrestrial cellular networks will be destroyed seriously. In this case, reliable communications should be provided by satellites or unmanned aerial vehicles. For example, in 2008 after Wenchuan 8.0 earthquake, the existing cellular network did not work at all and unmanned aircrafts were used to photograph the destroyed areas.

The tidal wave in Japan makes communication researchers aware of the importance of communications in disasters. Satellite phones can definitely be used in this scenario, however for a man in the street it is impossible to bring a satellite phone all the time. An economic way is to exploit multi-hop device-to-device (D2D) communications [44, 45]. More specifically, smart phones can be exploited to build a multi-hop D2D network. D2D protocol can be installed in smart phones as a software App. Moreover, unman aircrafts can be used as relay stations to facilitate the communications in disaster areas. It is worth highlighting that after earthquake, people may be buried in rubble and then it should be able to sense and detect very weak signals from rubble.

3.1.2 *Emergence communications*

Modern human society is threatened by terrorist attacks. When a city were attacked by terrorists, reliable communications cannot be realized relying on traditional cellular networks which are very vulnerable. Emergence communications can be provided by satellites, vehicles and unmanned aerial planes. These terminals can construct an ad-hoc network to support high quality emergence communication networks. This kind of communication must be anti-interference. In this scenario, the networks should be robust to interference and jamming, and it should also be flexible enough.

Flexibility is one of the most dominant characteristics of emergence communications. This characteristic requires the equipments of emergence communications should be light-weight platforms. For communication antenna arrays, it is hoped that antenna arrays should be collapsible or foldable to suit for crowed city environments. In modern city environments, localization is an important functionality of emergence communication systems. For example, sniffer localization is very challenging under high background noise and multiple reflections. Otherwise, localization of mobile users usually has great meanings. This task can be realized based on the received signals at base stations.

3.1.3 *Communications in polar region*

North polar region becomes more and more important for China as exploitation of north polar region can bring great economic benefits. Recently, it is discovered that the region of the arctic circle has about 13 percent of undiscovered oil reserves and 30 percent of undiscovered gas reserves. Resource exploitation results in competitions between countries. Communications play a fundamental role in the competition in the polar regions. High-capacity communication networks in polar region can provide necessary communication services to ships, gas installations, and also support other maritime activities, e.g., monitoring, surveillance, etc. As a result, polar region communications recently receive lots of attention from wireless researchers. The polar regions are far from China mainland and this fact makes building communication infrastructures more challenging.

It is obvious that satellite communications are the most natural choice for the communications in the polar region [46]. In the polar regions, the SGIN consists of satellites, handheld terminals, aircrafts and ships. The rescuers communicates with the control center via satellite phones. Considering electromagnetic compatibility it is really a challenging task to equip multiple radio stations in a limited room on the ship. On the other hand, because of its special latitude of polar region, satellite communications are more competitive than other communication technologies and it can also facilitate us to observe and receive signals from the universe. These facts also make the deployment and realization of SGINs in polar region much easier.

4 Platform based multi-antenna technologies

Multi-antenna arrays can be installed on different platforms. Different platforms have different physical limitations and application potentials. In addition, there are various functionalities of multi-antenna

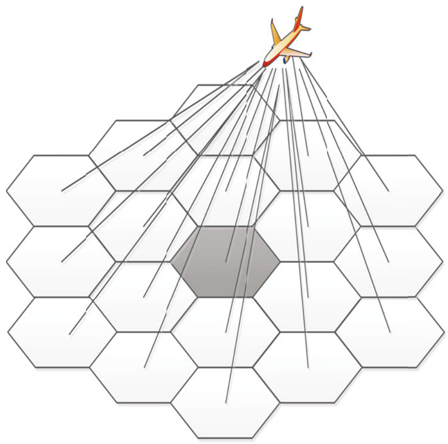

Figure 2 (Color online) Cellular aided internet connections for aircrafts.

technologies including transmission, localization, data collection and so on. In the following, we give a comprehensive overview of this issue.

4.1 Spaceborne multi-antenna technologies

It is widely accepted that via deployment of multiple antennas, satellite communications quality can be greatly improved including both the communications between satellites and the communications from satellite to ground [20, 47]. Moreover, the scale of the antenna arrays is usually very large. The phased array antenna equipped by satellites may consist of several hundreds of antenna elements [48]. Applying MIMO technologies in satellite communications is a very challenging task. The availability of MIMO technologies is determined by channel characteristics of satellite communications [49]. Generally speaking, satellite communications can be clarified into mobile and fixed satellites. For different kinds of satellites, different network technologies are needed to guarantee the availability of MIMO technologies. While multibeam technologies are always available, multibeam satellite can realize a wide range coverage [26, 50, 51].

Due to some imperfect characteristics, antenna elements on satellites may become aging and then array calibration is usually needed. For antenna calibration onboard satellites, computational complexity and algorithm overhead should be carefully considered. Considering the working frequency bands, in some cases MIMO technology cannot be applied directly. Then there are two design concepts that can be taken adavantage of to realize MIMO communications on satellites. Firstly, dual polarization antenna array can be used to realize MIMO communications [52]. Otherwise, a virtual antenna array can be constructed by a number of satellites i.e., a cluster of satellites [53]. The cooperation between satellites is quite similar to that of the cooperation between base stations, e.g., CoMP [35].

4.2 Airborne multi-antenna technologies

Nowadays, aircrafts are equipped with multiple antennas to guarantee the communication reliability [54]. Based on multi-beam beamforming design and the corresponding optimization, undesired interference can be cancelled by antenna arrays. As a result, communications between airplane and satellite can be enhanced. At high speed moving, wireless communications for airplane will suffer with large Doppler effects and communication quality will drastically decrease. Multi-antenna technologies are a promising technology candidate to mitigate the negative effects of Doppler frequency offsets.

In order to provide internet connection services on airplanes, there are various kinds of implementation schemes. One method is to take advantage of satellites. In this case, airplanes are equipped with antenna arrays to realize high quality communications between satellites. Another way is to take advantage of base stations in terrestrial cellular networks to realize internet connections [55] just as shown in Figure 2. In this case, from the viewpoint of interference it is also necessary to deploy antenna arrays on airplanes

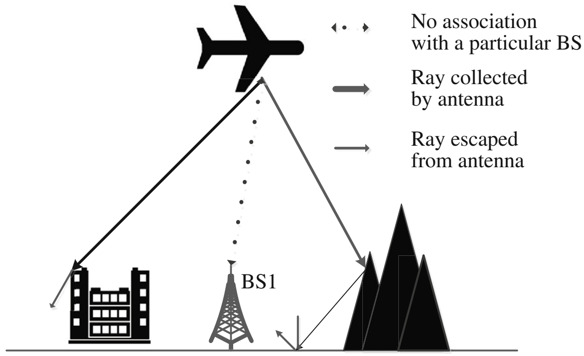

Figure 3 The connections between aircrafts and cellular base stations.

in order to mitigate unexpected interference signals from adjacent networks shown in Figure 3 [55]. Out of the coverage of cellular networks, this kind of connections can also be realized by other available access points [56].

As previously discussed aircrafts usually fly at very high speed and then large Doppler effects may destroy the reliable communications. Because of Doppler effects, the wireless channel becomes dispersive in frequency domain and the wireless channel is time varying in time domain. Relying on multi-antenna technologies space-time-adaptive processing (STAP) techniques can be used to mitigate unexpected interferences and mitigate the negative effects introduced by Doppler spectral spread meanwhile.

On aircraft platforms, synthetic aperture radar (SAR) is usually exploited to realize high-resolution remote sensing. In this case, multi-antenna technologies are also of critical importance. The resolution of imagining can be improved dramatically through using multi-antenna arrays. Moreover, if orthogonal waveforms are transmitted from each antenna, more degrees of freedom can be achieved and a much better performance is expected. This kind of technology is named as MIMO SAR. For MIMO SAR, orthogonal waveforms are very important. Because if orthogonality cannot be guaranteed, for area targets the imaging resolution performance will degrade seriously.

4.3 Shipborne multi-antenna technologies

China has great ambitions in exploiting the sea in the coming 10 years. Even for the offshore regions, cellar networks cannot provide satisfied coverage. Additionally, affected by sea clutters communications over sea are vulnerable to these natural interferences. As far from mainland, communications between ships are more challenging than terrestrial cellular communications.

From a practical viewpoint, it is natural that multiple antennas can be equipped on a ship in order to realize reliable communications between ship and ship or between ship and satellite or between ship and aircraft. On the other hand, exploiting antenna arrays is a very effective way to detect some targets. In the practical shipborne communication systems, ships are widely equipped with phased arrays to detect targets.

For shipborne information systems, an important technical trend is to integrate radar systems and communication systems. Onboard many radio stations are installed in very narrow spaces. In some cases, due to space limitation and the problem electromagnetic compatibility, the radar system and communication system cannot work simultaneously. As a result, when information will be transmitted, the radar system should be turned off first. It is obvious that this case is very dangerous. As a result, it is of critical importance how to design a waveform that is both suitable for signal detection and information transmission. In addition, it is also valuable how to realize different types of communications using software defined radio (SDR) architecture.

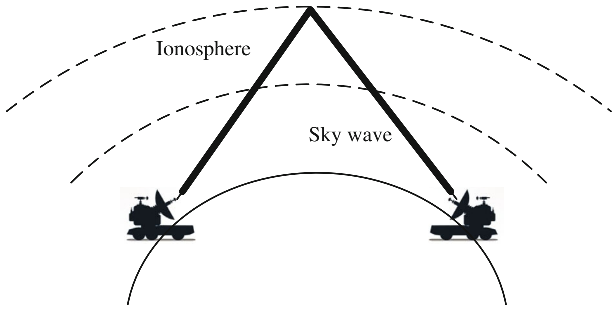

Figure 4 Scatter communications between vehicles equipped with antenna arrays.

4.4 Vehicular multi-antenna technologies

In modern societies, vehicular communications play an important role and it is the basis of smart city [57]. Multi-antenna array can be mounted at the top of a vehicle to facilitate the communications between vehicles and satellites. For example, antenna arrays amounted on high speed trains can provide high quality network connections [58]. Vehicle to vehicle (V2V) communications are a flexible means to deliver information in an ad-hoc manner. V2V communications can realize many fancy applications. For example, in Beijing some research institutes want to take advantage of V2V communications to monitor the air condition. In Beijing, there are only a very limited number of monitoring sites for air condition monitoring, while in Beijing it is crowd of cars. Then V2V networks can cover the whole city and implement a sufficient monitoring task.

Scatter communications is another important application of vehicle mounted antenna array. Exploiting the refection of electromagnetic wave in ionosphere, long distance communications can be realized as shown in Figure 4. Scatter communications are also robust to interference and immune to heavy weather conditions. Vehicular scatter communications can build a data link with 2 Mbps in a range of 140 km. As there is no need for the satellites to relay information it releases satellites' resources and meanwhile the communication procedure becomes more secure and more reliable. Deploying antenna arrays can also greatly improve the quality of the communications between vehicles and satellites [59].

4.5 Underwater multi-antenna technologies

Underwater communications are based on acoustic waves instead of electromagnetic waves, as the later has deep fading in water. Generally speaking, underwater communications are more complicated and challenging than their counterpart in air. Recently, companying the exploitation in the sea underwater communication technologies have received more and more attention. Different from the mature cellular network communications, to the best of the authors' knowledge, there are tremendous space in the research on underwater communications.

It is an important research issue how to use multi-antenna arrays to detect underwater targets. For example, an effective method to localize underwater sources is to use beamforming based on matched field processing [60]. Just as shown in Figure 5 owed array sonar can be used to detect the underwater target. Owed array sonar is an application of multi-antenna technologies underwater. As underwater acoustic channels are very complicate, which vary according to water temperature and depth of water, acoustic antenna array designs must be robust enough to model uncertainties.

5 Combinations of multi-antenna technologies and other advanced technologies

5.1 Physical layer network coding based applications

For wireless networks, interference is the most dominant factor limiting network capacity. To avoid serious mutual interference between simultaneous communications, some scheduling schemes are usually

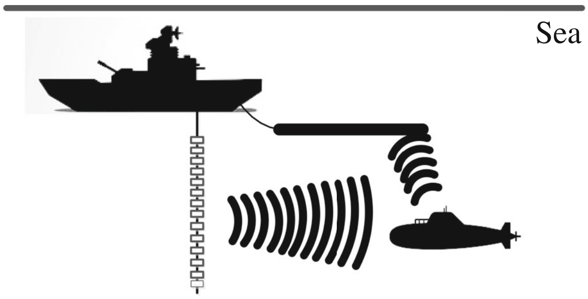

Figure 5 Owed antenna arrays equipped on a ship.

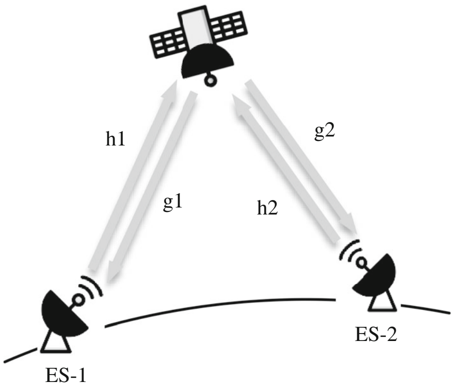

Figure 6 Physical layer network coding based satellite communications.

needed. Based on the classical network protocols, to avoid mutual interference traditionally it needs four phases to exchange information between two sources via a relay node. The scheduling protocol to avoid interference is at the cost of resource efficiency.

Recently, it is revealed that physical layer coding is an effective technology for nodes to exchange information more effectively. Based on physical layer network coding, the information exchange needs two phases. In the first phase, two sources transmit their signals to the relay. The relay receives the superimposed signals. In the second phase, the relay broadcasts the received signal to the two sources. As each source node perfect knows what they transmit in the first phase, the desired signal at each node can be recovered.

Furthermore, all the involved nodes can be equipped with multiple antennas. The combination of multi-antenna technologies and physical layer coding can greatly improve spectrum efficiency. This strategy can be understood as a soft combination of uplink multi-user MIMO and downlink multi-user MIMO. More specifically, the relay node can be taken as a base station. The first phase is the uplink and the second phase is the downlink. The main difference from commercial cellular networks is that the base station does not decode the signals and directly forward the received signals to the two nodes. Unsurprisingly, as shown in Figure 6, physical layer network coding can be used to improve the spectral efficiency of satellite communications [61–63].

5.2 Physical layer security oriented applications

Security is definitely one of the most important issues of networks [64]. Recently, physical layer security has attracted lots of attention. Different from encryption based network security, physical layer security realizes security at the signal level. Specifically, based on physical layer security technology the signal at eavesdropper is lower than a threshold. Then the SNR at eavesdropper is so low that it cannot successfully decode the eavesdropped information [65]. As a result, network security is realized.

Multi-antenna technologies can inherently support physical layer security. Equipped with multiple

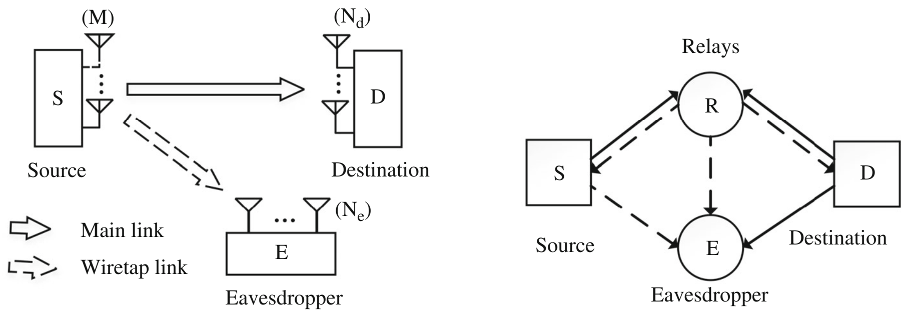

Figure 7 Network models for physical layer security.

antennas, the transmitter can take advantage of beamforming to focus on signals to the legitimate user and meanwhile steer the side lobe to the eavesdroppers. Moreover, based on multi-antenna an artificial jammer or a relay can be introduced into the system to further improve security performance. Multi-antenna means more degrees of freedom and thus a better security performance can be achieved. As shown in Figure 7, there are various network models when considering physical layer security [66]. All of these design concepts in Figure 7 can be directly applied to satellite communications.

5.3 Cloud computing based applications

Recently, a novel network architecture named C-RAN is proposed by China mobile the biggest operator in China. C-RAN is a distributed antenna system. In a typical C-RAN, the base band units (BBUs) are separated from radio fronts. The remote radio heads (RRHs) are randomly distributed in the network coverage area. This network architecture can make cellular networks more green as it can greatly save energy via reducing the number of air-conditioning. C-RAN can be interpreted as the extension of cloud concept to mobile networks [67]. In addition to energy saving, C-RAN also permits more flexible network optimization operations among the BBUs in a BBU pool.

With a huge number of RRHs, the distance between mobile user and radio interface will be reduced and corresponding transmit power can be reduced. Then network capacity will surge. Strictly speaking, distributed antenna system is not a new idea, while combining with cloud computing at BBU pool and network virtualization technologies [68], C-RAN becomes a novel and impelling technology for future network architectures. C-RAN will be a necessary ingredient of future SGINs. It is worth highlighting that the distributed antenna deployment is definitely a variant of multi-antenna technologies. Distributed beamforming designs and distributed transceiver optimization become more and more important for C-RAN. Especially considered the involved large scale optimization, transceiver designs and resource allocation have strict limitations [69].

Interestingly, a similar idea for the distributed operation can also be applied to radar systems. For target detection, a detection task can be realized by using a number of low cost small radars instead of a big radar. Based on this logic, the whole radar system will become more robust. Of course, cooperation between these low cost radars should be built on effective and reliable distributed algorithms. In addition, the idea of software defined functionalities in C-RAN can also be introduced into satellite networks [67].

5.4 Cooperative communication based applications

To the best of authors' knowledge, cooperative communication is first proposed for distributed sensor networks. Later this technology is introduced into cellular networks. Aided by relay nodes, the coverage of base station can be improved significantly. At the relay nodes, there are three different forwarding strategies, i.e., decode-and-forward strategy, amplify-and-forward strategy and compressed-and-forward strategy. It is meaningless to say which one is better without specifying network configurations. The applications of relay technologies in cellar networks have spurred the search for cooperative communications, however cooperative communications for cellular networks are really a complimented techniques. The most useful method to increase network capacity is to increase the density of base stations.

Dual-hop MIMO relaying and multi-hop MIMO relaying have more and more applications. In nature, transceiver optimization for multi-hop MIMO relaying networks is not as difficult as it looks like. The optimal diagonalizable structures of transceivers can greatly simplify the considered optimization problems [36]. In other words, successful designs can reduce the cost of cooperation. Cooperative communications can be directly applied to satellites [48]. On satellites the signals can be decoded first or direly forwarded to the destination [70, 71]. It should be highlighted that availability of cooperative communications are based on CSI sharing and it may incur significant overheads. As there is no free lunch, cooperation or not depends on the tradeoffs between cooperation costs and performance gains.

5.5 Massive MIMO based applications

In future 5G, massive MIMO technologies are expected to be used to improve spectrum efficiency greatly. We would like to highlight that except information transmissions massive MIMO has a wide range of applications. Massive MIMO technology can be taken advantage of into improving the data fusion performance. For a distributed sensor network, information is collected by distributed sensors and then the sensors forward their sensed signals to a data fusion center, such as an aircraft or a mobile vehicle [72]. The data fusion can be equipped with a large number of antennas and thus a much better performance can be achieved via very low complexity fusion algorithms. In other words, massive MIMO technologies can simplify the data collection task for a moving data fusion center such as a unmanned aerial vehicle.

Similarly, for cognitive radio networks, the second user can sense the spectrum holes more accurately by using a large antenna array. On satellites, phased array antennas construct a large scale antenna array and then some ideas of the massive MIMO technologies for terrestrial communications can be directly applied. This fact means that similarly to the massive MIMO systems in terrestrial communication networks linear operations e.g, zero-forcing precoder will achieve the optimal performance on the satellites with a large antenna array. Moreover, for underwater acoustic communications, a large underwater antenna arrays can be exploited to realize much better estimation performance. The corresponding calibration algorithms should also be carefully designed in order to reduce the performance loss.

5.6 High frequency band applications

For wireless communications, the most direct and effective method to increase data rate is to use more frequency bands. The large amount of available millimeter wave (mm wave) bands i.e., form 30GHz to 300GHz are very attractive for high data rate transmissions. Recently, mm wave communication has attracted more and more research interest due to its great potentials in transmission rate improvement.

Here we would like to highlight that mm wave propagation channels are significantly different from traditional microwave channels. Mm wave channels usually have excessive path and penetration losses that may destroy wireless communications. In addition, mm wave channels are characterized by cluster multi-path structures and dominant LOS components.

An effective method to overcome these weaknesses is to use multi-antenna beamforming. At high frequency bands, antenna elements can be produced in a very small size and a terminal can be equipped with much more antenna elements. This fact makes multi-antenna beamforming much preferred for mm wave communications. For mm wave communications, low cost hybrid beamforming designs are much preferred. As shown in Figure 8 hybrid beamforming design consists of two parts, i.e., a analogy part and a digital part. The number of ADCs should be strictly limited in order to save the hardware cost. In the analogy part, each antenna can only adjust signal phases. On the other hand, in the digital part, both amplitudes and phases can be adjusted. The common logic to optimize hybrid beamforming is to approximate all digital beamforming design as accurately as possible.

Furthermore, tera Hertz (THz) communications are also characterized by very high data transmission rates. In SIGNs, THz communications also have many important applications. For example, two aircrafts can exchange their huge amounts of information in a very short time slot using THz communications when they are near enough. Moreover, THz communications can also facilitate the information exchange between satellites in a very short time slot in their moving orbits.

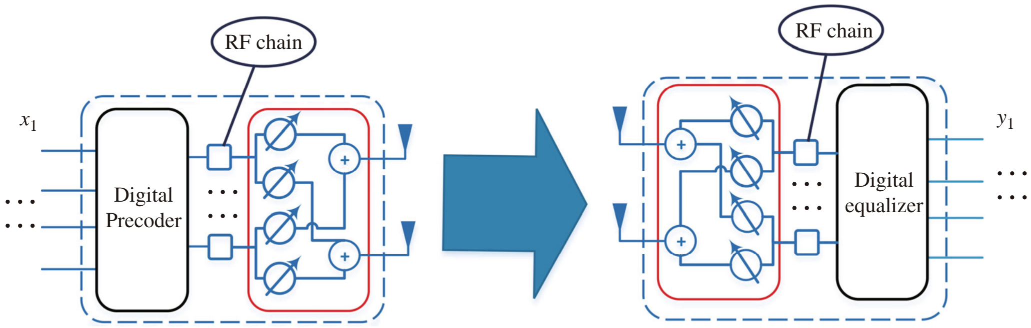

Figure 8 (Color online) The diagram of hybrid beamforming.

6 The challenges of multi-antenna technologies in SGINs

Based on the previous discussions, it is obvious that multi-antenna technologies are important and necessary for SGINs. The performance gains of multi-antenna technologies are usually at the cost of high computational complexity and hardware cost. Multi-antenna technologies not only depend on signal processing technologies but also are related to circuit technologies, antenna technologies, etc. Then a question is what kind of signal processing technologies we are desired to have. Different from the surplus hardware resources in some terrestrial communications, space communications or satellite communications are subjected to very limited payloads. Moreover, especially for real time applications there will exist strict requirements and limitations on the algorithm complexity and communication delays.

Low complexity and high performance are usually contradictory with each other. In the existing works, a logic to improve performance is to jointly design as many parameters as possible. From a theoretical viewpoint, it is straightforward that jointly optimizing more parameters can positively improve the system performance. Unfortunately, in practice this logic is meaningless as the cost of joint designs is usually more than we can offer. For SGINs the high performance signal processing algorithms with high complexity are useless, which may be hardware killer applications.

As discussed in the existing literature [36], for MIMO systems variables are extended to matrix variables, however it seems that we never directly optimize each element of the matrix variable. In most cases, we try to find its optimal structures based on which the number of variables will dramatically reduced and the considered optimization problem will be simplified. Moreover, in this procedure some important physical meanings will be revealed as well. Inspired by this fact, the structure information should be carefully investigated including the mathematical structures of the considered optimization problems, the signal structures, the network structures, etc. Structure aware optimization is much preferred by future SGINs, which can drastically simplify the considered optimization problems in SGINs.

Furthermore, for SGINs strict network wide synchronization is very difficult. To accommodate heterogeneous traffics with significantly different delays [43], asynchronous distributed signal processing algorithms will be very important. Particularly, considering different network interfaces, for information transmissions some different subnetworks may be virtualized as super nodes. Unfortunately, these operations are usually at the cost of the synchronization. Considering different terminals usually have different delay requirements and SGINs are also multi-layer heterogeneous networks, it is really a difficult task to realize strict synchronization between different terminals in different subnetworks. To the best of the authors' knowledge synchronization for SGINs ia still a largely open problem.

7 Conclusion

Integration and converge are the distinct trends of the development of information networks. SGINs will epitomize almost all the requirements for information networks. Multi-antenna technologies act as the most important physical layer enabling technology and receive a lots of attention. For future SGINs, multi-antenna technologies will be much more important. In this paper, a comprehensive overview on multi-antenna technologies is given. In particular, we discussed in depth its potentials and challenges for SGINs. Especially, we elaborated on its important application scenarios including cases in disasters, in city emergence and in polar region. Furthermore, the applications of multi-antenna technologies on different platforms were investigated. Moreover, the combinations of multi-antennas and other advanced technologies were also considered. It is undoubted that multi-antenna technologies are an important ingredient for SGINs. The related issue will be a hot topic in the future research.

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Conflict of interest The authors declare that they have no conflict of interest.

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