Global Smartphone Technological Innovation Capacity Analysis Based on Latent Semantic Indexing and Vector Space Model Method

ZHANG Yuwen, *CHEN Wanming**

College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing 211106, P. R. China

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Abstract: This paper analyzes the global competitive landscape of smartphone technological innovation capacity using the latent semantic indexing (LSI) and the vector space model (VSM). It integrates the theory of technological ecological niches and evaluates four key dimensions: patent quality, energy efficiency engineering, technological modules, and intelligent computing power. The findings reveal that USA has established strong technological barriers through standard-essential patents (SEPs) in wireless communication and integrated circuits. In contrast, Chinese mainland firms rely heavily on fundamental technologies. Qualcomm Inc. in USA and Taiwan Semiconductor Manufacturing Company (TSMC) in Chineses Taiwan have built a comprehensive patent portfolio in energy efficiency engineering. While Chinese mainland faces challenges in advancing dynamic frequency modulation algorithms and high-end manufacturing processes. Huawei Inc. in Chinese mainland leads in 5G module technology but struggles with ecosystem collaboration. Semiconductor manufacturing and radio frequency (RF) components still rely on external suppliers. This highlights the urgent need for innovation in new materials and open-source architectures. To enhance intelligent computing power, Chinese mainland firms must address coordination challenges. They should adopt scenario-driven technological strategies and build a comprehensive ecosystem that includes hardware, operating systems, and developer networks.

Key words: smartphone chips; technological innovation capacity; latent semantic indexing (LSI); vector space model (VSM)

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0 Introduction

Technological barriers and core technology restrictions imposed by developed countries have significantly constrained the chip development efforts of Chinese mainland firms, including Huawei Inc.[1-2]. Assessing the technological innovation capacity in smartphone chip development is crucial for evaluating the competitive strength of Chinese mainland firms. It also helps identify opportunities to enhance core chip technologies and fosters the establishment of an independent and open ecosystem driven by patent-based innovation.

Research on smartphone chips primarily focuses on their technical attributes and research and development (R&D) applications. Yousif et al.[3] proposed an adaptive multiple-input multiple-output (MIMO) free-space optical (FSO) link. Xiao et al.[4] explored smartphone-based detection technologies, including microscopic imaging, colorimetric sensing, fluorescence imaging, and chemiluminescence sensing. Elsayed[5] introduced a method integrating pulse-position modulation (PPM) and dense wavelength-division multiplexing (DWDM) to enhance the efficiency and reliability of intelligent device communication systems. Li et al.[6] developed a

*Corresponding author, E-mail address: cwmnuaa@163.com.

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robust filtering pedestrian navigation method that integrates smartphone and satellite positioning for improved fault repair. Elsayed[7] demonstrated the feasibility of hybrid optical modulation techniques in DWDM-FSO hybrid links, significantly enhancing the efficiency of optical wireless and fiber-optic communication systems. Upadhyay et al.[8] investigated smartphone sensing paradigms for modern medical point-of-care (POC) testing, while Al-Sabaeei et al.[9] examined smartphone-based sensor technologies for pavement condition monitoring. Despite these advancements, existing research remains largely confined to specific chip categories and their applications, such as communication, sensing, and optical imaging. It lacks a comprehensive analysis of major technological domains. This gap limits a holistic understanding of critical technology distributions and evolutionary trends, restricting broader insights into the innovation landscape of smartphone chips.

Patent analysis primarily employs mathematical and statistical methods to extract, process, and analyze patent information, including titles, abstracts, claims, and international patent classification (IPC) codes. This approach reveals current technological landscapes and predicts future trends in patent development. For instance, Jiang[10] used IPC codes combined with *K*-means clustering to identify key technological domains and assess patent value in smartphone media technologies. Li et al.[11] integrated patent classification analysis to develop a framework for monitoring disruptive innovations in smartphone technology. Lee et al.[12] evaluated the technological competitiveness of global industry leaders in semiconductor nanotechnology by analyzing the growth rate of patent registrations. Han et al.[13] utilized clustering analysis and the log likelihood ratio (LLR) algorithm to examine the evolutionary trajectory of 5G technology and its development trends. Cammarano et al.[14] explored the perceptual quality of smartphones, emphasizing its reliance on three critical components: application processors, camera modules, and image sensors.

Existing patent analyses primarily reveal technological trends within specific domains but offer limited insights into technological competition, market positioning, and R&D capabilities in smartphone chip development. Text clustering algorithms, such as those based on IPC and *K*-means, face inherent challenges in processing cross-linguistic patent data, handling large-scale patent datasets, and conducting semantic dimensionality reduction. To address these limitations, this study adopts a patent-granted data perspective and employs advanced text analysis methods, including latent semantic indexing (LSI) and vector space model (VSM). Grounded in technological niche theory, we systematically assess the global innovation capacity of smartphone chips across four key dimensions: patent quality, energy efficiency engineering, technological modules, and intelligent computing power. This research provides valuable insights for the sustainable development of smartphone technologies and offers strategic guidance for Chinese mainland firms to identify emerging technological trajectories and accelerate breakthroughs in chip R&D.

1 Research Design

1.1 Data source and retrieval method

The patsnap global patent database spans 170 countries and regions. It includes about 180 million patent records. This database offers a dependable data source and robust analytical tools for extensive patent analyses[15]. In this study, we utilized the patsnap global patent database and its analytical tools. Technical experts aided in gathering patent literature on smartphone chip technology. Patent grants signify technological breakthroughs in specific domains. Patents require novelty, inventiveness, and practicality. Among patent types, invention patents prioritize innovation in products and methods over design patents and utility models. Hence, invention patents better represent the technological strength of a region or innovator and offer higher analytical value. Smartphones possess independent operating systems and incorporate various electronic chip devices. Fig.1 shows the primary chip technology used in modern smartphones.

Based on the chip classification shown in

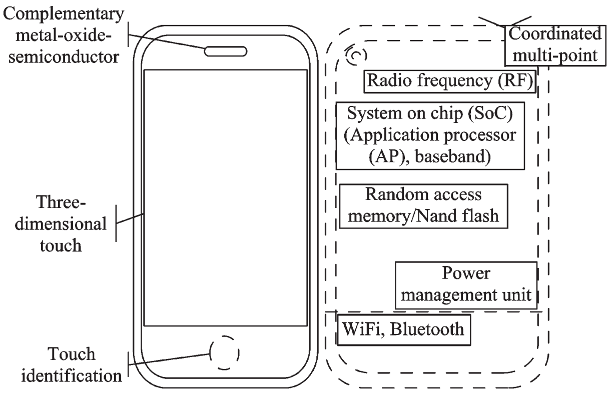

Fig.1 Main components of smartphone chip technology

Fig.1, the search topics (title and keywords) were determined, as presented in Table 1. These topics were identified by reviewing relevant literature on mobile phone chips[16-18] and by consulting experts knowledgeable in mobile phone chip technology, intellectual property rights, and related fields. To ensure the accuracy and comprehensiveness of the search results, the search was conducted by combining the selected search terms with IPC classification numbers pertinent to mobile phone chip technology. These IPC numbers were identified through iterative searches and meticulous examination of relevant patent literature during the preliminary research stage[19-20]. The combination of targeted search terms with IPC classification numbers facilitates a more thorough and precise retrieval of pertinent patent literature.

Table 1 Categories of smartphone chips (including design and manufacturing), main functions, and search terms

Chip category	Main function	Search term
SoC	Logic operations, signal and protocol handling	SoC/System on chip
AP	Mobile operating system	AP/Application processor
Baseband	Controlling software applications	baseband
RF	Radio frequency transmission and reception	RF/Radio frequency/RFCOMS
Storage	Storing mobile programs and application data	RAM/NAND FLASH
Camera	Converting light signals into electrical signals	CMOS
Touchscreen	Multi-touch on the display screen graphics	3D touch
Fingerprint recognition	Fingerprint detection and precise recognition	Touch ID
Power management	Providing power required by the main chip	Power management unit
Connectivity chip	Wireless connectivity features	Wireless connectivity/WIFI/ Bluetooth
Antenna	Devices inside the phone for signal reception	soft defined radio /CoMP
Design and manufacturing	3D transistors, BCD technology chip(ultra-thin)	FinFET 3D/ Bipolar-CMOS-DMOS/BCD

Using the search terms listed in Table 1 and the corresponding IPC classification codes, patent data were collected for the period from January 1, 1993, to November 30, 2024. This timeframe was selected because the IBM Simon, widely recognized as the first smartphone, was introduced in 1993. The search specifically targeted "granted invention patents", and only patents with the legal status "granted and rights reinstated" were included. Patents with invalid statuses, such as "expired" "terminated" "abandoned" "unpaid maintenance fees" "withdrawn" or "fully revoked", were excluded. Additional filtering and deduplication procedures were conducted using the Patsnap system, resulting in a final dataset comprising 126 340 valid patent grants.

1.2 Research method

1.2.1 LSI algorithm

Text clustering algorithms, such as LSI, were used to analyze the titles, abstracts, and claims in patent documents. This process extracted diverse phrase forms. The extracted phrases, which were closely related to core smartphone chip concepts, were then grouped into multiple clusters. This grouping generated an innovation keyword map.

The principle of LSI[21-22] involves these key steps: (1) Preprocessing patent texts by tokenization and removing stop words; (2) constructing a document-term matrix with rows as documents, columns as terms, and elements as term frequency or weights; (3) applying dimensionality reduction techniques, such as singular value decomposition

(SVD)[23], to convert the high-dimensional matrix into a lower-dimensional topic-term matrix. This decomposes the original space into multiple lower-dimensional topic spaces, each representing a latent semantic topic (Fig.2); (4) identifying the most relevant keywords for each topic to characterize that topic space; (5) converting query statements into low-dimensional topic vectors for information retrieval, and calculating similarity between these vectors and topic spaces to identify the documents most relevant to the query.

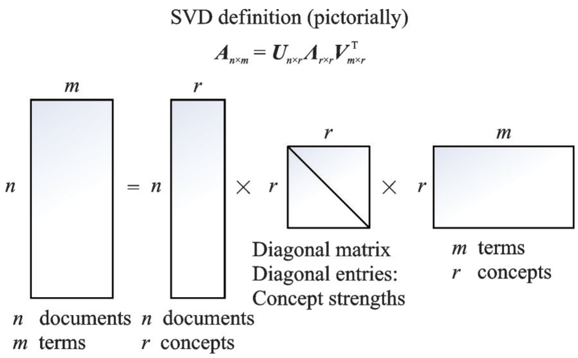

Fig.2 Matrix definition in SVD for LSI algorithm

Specifically, consider a text set comprising n documents and utilizing m words. These word-document relationships are represented as a matrix denoted by $\boldsymbol{A}_{mn}=[a_{ij}]$, where a_{ij} represents the weight of word i in document j. Typically, a local weighting model and a global weighting model are employed to address the relative importance of word i within a specific document and across the entire document set, respectively, expressed as $a_{ij}=L(i,j)*G(i)$. Here, $L(i,j)$ denotes the local weighting function of word i in document j, reflecting the frequency of word i in document j, and is defined as $L(i,j)=tf(i,j)$. The parameter t corresponds to the term i. The function f is a term frequency function, representing the frequency of a specific term's occurrence in a document. The function itself is denoted by the abbreviation tf, which stands for term frequency. $G(i)$ represents the global weighting function of word i across the entire document set, defined as $G(i)=\log_2\left(\frac{n}{df(i)}+1\right)$, where $df(i)$ indicates the number of documents in the set that contain word i, i.e., the document frequency of word i. Subsequently, the matrix $\boldsymbol{A}$ is decomposed into three matrices for root matrix compression, expressed as $\boldsymbol{A}=\boldsymbol{U\Lambda V}^{\mathrm{T}}$, as shown in Fig.2.

The matrix $\boldsymbol{A}$ is a $n\times m$ matrix (with n documents and m words). $\boldsymbol{U}$ is a $n\times r$ orthogonal matrix representing the left singular vectors of the words, which indicates the association between words and latent topics. $\boldsymbol{\Lambda}$ is a $r\times r$ diagonal matrix containing the singular values (arranged in descending order), representing the importance of each latent topic. $\boldsymbol{V}^{\mathrm{T}}$ is a $r\times m$ orthogonal matrix representing the right singular vectors of the documents, indicating the association between documents and latent topics. To approximate the original matrix $\boldsymbol{A}$ with a lower-dimensional representation, the top k singular value-related components are selected from $\boldsymbol{U}$, $\boldsymbol{\Lambda}$, and $\boldsymbol{V}^{\mathrm{T}}$. Specifically, $\boldsymbol{U}_k$ denotes the first k columns of $\boldsymbol{U}$, with a shape of $m\times k$; $\boldsymbol{\Lambda}_k$ is a diagonal matrix composed of the top k singular values, with a shape of $k\times k$; and $\boldsymbol{V}_k$ denotes the first k columns of $\boldsymbol{V}$, with a shape of $n\times k$. The reduced-dimensional matrix is then given by $\boldsymbol{A}_k=\boldsymbol{U}_k\boldsymbol{\Lambda}_k\boldsymbol{V}_k^{\mathrm{T}}$, representing the inherent lowest-dimensional approximation of the original matrix $\boldsymbol{A}$. The choice of dimensionality depends on the complexity of the dataset and its semantic information. The size of dimension k can be determined through information entropy and dimensionality reduction, such that the proportion $\sum_{i=1}^{k}s_i^2\Big/\sum_{i=1}^{r}s_i^2$ is not less than 80% (90% was selected in this study), where s_i represents the singular values, and r is the rank of the matrix.

Due to space constraints, we chose eight recent patent documents from the wireless communication sector of smartphone chip technology as examples for the LSI algorithm. First, patent texts were preprocessed, relevant keywords were extracted, and a text matrix was constructed, as shown in Table 2.

A threshold was set to select keywords appearing more than three times for conducting a weight analysis of the "term-document" matrix. Matrix $\boldsymbol{A}$, calculated using $a_{ij}=L(i,j)*G(i), L(i,j)=tf(i,j)$, $G(i)=\log_2\left(\frac{n}{df(i)}+1\right)$, is presented in Table 3.

Table 2 Preprocessing of example texts for the LSI algorithm in the field of smartphone chip wireless communication

Patent number	Extracted keyword
CN102006653A	Access control: access state, beacon frame, service set identifier, access delay
CN101854198A	Multi-antenna transmission: space-time coding, antenna grouping, beamforming, diversity gain
CN101730257A	Signal transmission: primary carrier frequency, synchronization channel, broadcast channel
CN101998558A	Cell handover: user equipment, cell handover, air interface resources, handover delay
CN101945398A	Network planning: node position, traffic load, antenna direction, channel allocation
CN101810011A	Multicast communication: bandwidth allocation, multicast channel, predefined algorithm
CN101741792A	Signal processing: orthogonal frequency division multiplexing (OFDM), arctangent function, signal compression, peak-to-average power ratio
CN101868001A	UE access: local network, radio bearer, access network

Table 3 Term-document matrix in the field of wireless communication for smartphone chips

Keyword	Patent 1	Patent 2	Patent 3	Patent 4	Patent 5	Patent 6	Patent 7	Patent 8
Access state	3.17	0.00	2.32	0.00	1.87	1.59	0.00	0.00
Beacon frame	3.17	0.00	0.00	2.32	0.00	0.00	0.00	1.87
Space-time coding	0.00	3.17	0.00	0.00	0.00	0.00	1.38	0.00
Beamforming	1.38	3.17	0.00	0.00	3.17	1.59	0.00	0.00
Synchronization channel	0.00	0.00	3.17	0.00	0.00	0.00	0.00	1.59
Cell handover	1.22	2.32	0.00	3.17	0.00	0.00	2.32	0.00
Antenna direction	0.00	0.00	0.00	0.00	3.17	0.00	0.00	3.17
Bandwidth allocation	0.00	1.09	0.00	0.00	0.00	3.17	0.00	0.00
OFDM	0.00	0.00	1.09	0.00	0.00	0.00	3.17	0.00
Local network	0.00	0.00	0.00	0.00	1.59	0.00	0.00	3.17
Access delay	2.32	0.00	0.00	2.32	0.00	2.32	0.00	0.00

Furthermore, SVD was applied to the matrix for dimensionality reduction, retaining the first three topics (k=3). Topic 1, labeled as "access-related", includes high-weighted terms such as access state, beacon frame, synchronization channel, local network, and access delay, covering Patents 1, 3, 4, and 8. Topic 2, labeled as "antenna technology", encompasses high-weighted terms like space-time coding, beamforming, and antenna direction, covering Patents 4 and 5. Topic 3, labeled as "signal and bandwidth", includes high-weighted terms such as OFDM and bandwidth allocation, covering Patents 6 and 7.

1.2.2 VSM algorithm

Phrases closely associated with the core concepts of smartphone chips were grouped into multiple clusters. Each cluster was further refined to establish a secondary hierarchical structure, facilitating detailed keyword-based analysis. The VSM algorithm[24-25] was employed to identify specific keywords and phrases strongly linked to these core concepts, as well as their frequency of occurrence.

The VSM algorithm represents queries and documents as vectors. It evaluates their similarity by calculating the cosine similarity between these vectors. Specifically, the algorithm assumes a predefined set of terms. Both queries and documents can then be represented as vectors composed of these terms. For a document $\boldsymbol{D}=(w_1, w_2, \cdots, w_n)$, w_i represents the weight of term t_i, reflecting its importance in the document, also referred to as its term weight. Similarly, the query $\boldsymbol{Q}=(w_{q_1}, w_{q_2}, \cdots, w_{q_n})$ is represented as a vector, where w_{q_i} represents the weight of term t_i in the query $\boldsymbol{Q}$. The weight w_i of term t_i is calculated using the combination of term frequency (TF) and inverse document frequency (IDF), as follows

$$W_{d_i}=\mathrm{TF}_i{*}\mathrm{IDF}_i=\frac{\mathrm{Frq}_i}{\mathrm{Max}_j\mathrm{Frq}_j}*\log\frac{N}{n_i} \tag{1}$$

where Frq_i represents the frequency of term t_i in document $\boldsymbol{D}$; $\mathrm{Max}_j\mathrm{Frq}_j$ denotes the frequency of the term t_j with the highest occurrence in document $\boldsymbol{D}$, which is used for normalizing term frequencies; n_i represents the number of occurrences of t_i in document $\boldsymbol{D}$; and N represents the total number of terms in document $\boldsymbol{D}$, where $i,j\in\{1,2,\cdots,n\}$. Additionally, w_{q_i} is shown as

$$w_{q_i}=\mathrm{TF}_{q_i}=\frac{\mathrm{Frq}_{q_i}}{\mathrm{Max}_j\mathrm{Frq}_{q_j}} \tag{2}$$

where Frq_{q_i} is the number of occurrences of term t_i in the query $\boldsymbol{Q}$, and $\mathrm{Max}_j\mathrm{Frq}_{q_j}$ the frequency of the most frequent term in the query $\boldsymbol{Q}$.

Therefore, the degree of correlation between $\boldsymbol{D}$ and $\boldsymbol{Q}$ is represented by the cosine of the angle between the corresponding vectors, shown as

$$\mathrm{SIM}(\boldsymbol{D},\boldsymbol{Q})=\cos\theta=\frac{\sum_{i=1}^{n}W_{d_i}*w_{q_i}}{\sqrt{\sum_{i=1}^{n}W_{d_i}^2*\sum_{i=1}^{n}w_{q_i}^2}} \tag{3}$$

The term $\sum_{i=1}^{n}W_{d_i}*w_{q_i}$ represents the product of the document weight and the query weight across corresponding dimensions. $\sqrt{\sum_{i=1}^{n}W_{d_i}^2}$ represents the magnitude of the document vector, while $\sqrt{\sum_{i=1}^{n}w_{q_i}^2}$ represents the magnitude of the query vector. The cosine similarity score ranges between $[-1,1]$, where 1 indicates a perfect match between the document and the query, 0 indicates no similarity, and -1 indicates complete opposition. Through the construction of the VSM, the weight calculation fully considers the importance of term t_i in the entire document collection, enabling precise ranking and retrieval of documents. This approach contributes to the detailed analysis of smartphone chip technology in specific domains.

Due to length constraints, we selected six latest patent documents related to battery technology in smartphone chips for the VSM calculation.

First, the patent texts were preprocessed, relevant keywords were extracted, and word frequencies were calculated. Keywords appearing more than three times were chosen to construct the text matrix, as shown in Table 4.

Secondly, calculate the weights of the text matrix according to word frequency and normalization, namely $W_{d_i}=\mathrm{TF}_i*\mathrm{IDF}_i$, as shown in Table 5.

Furthermore, according to Eq.(3), the cosine similarity is 0.323 between Patent 1 and Patent 2, 0.938 between Patent 4 and Patent 5, and 0.037 between Patent 3 and Patent 6. Patents 1 and 2 share the term "smartphone battery", indicating a moder-

Table 4 Text preprocessing for VSM calculation in battery-related fields of smartphone chip technology

Patent number	Keyword (word frequency)
CN110672231A	Smartphone battery (4), air temperature (6)
CN115995870A	Smartphone battery (3), charging management (5)
CN116995786A	Wireless charger (5), charging management (3)
CN119519050A	Solar energy (4), charging management (4)
CN109901333A	Solar energy (3)
CN113068363A	Radiator (4), charging management (5)

Table 5 Document weights in battery-related fields of smartphone chips

Keyword	Patent 1	Patent 2	Patent 3	Patent 4	Patent 5	Patent 6
Smartphone battery	0.318	0.286	0.000	0.000	0.000	0.000
Air temperature	0.778	0.000	0.000	0.000	0.000	0.000
Charging management	0.000	0.176	0.106	0.176	0.000	0.176
Wireless charger	0.000	0.000	0.778	0.000	0.000	0.000
Solar energy	0.000	0.000	0.000	0.477	0.477	0.000
Radiator	0.000	0.000	0.000	0.000	0.000	0.622

ate technological link in battery-related fields. Patents 4 and 5 share "solar energy", reflecting a close focus on solar charging technology. Although Patents 3 and 6 both include "charging management", their emphases diverge significantly: Patent 3 addresses wireless charging, while Patent 6 targets radiator technology.

1.2.3 Method comparison

Compared with traditional methods such as the bag of words (BoW) model, K-means[26], and Boolean retrieval models, LSI and VSM offer distinct advantages. Specifically, these methods extract semantic relationships using term frequency-inverse document frequency (TF-IDF) weighting and SVD dimensionality reduction. They effectively handle high-dimensional sparse data and mitigate noise in patent documents. Additionally, LSI and VSM are well-suited for large-scale data analysis, markedly improving clustering efficiency and accuracy. Furthermore, these approaches enable uniform processing of multilingual patent data. Thus, LSI and VSM prove highly applicable for analyzing global smartphone technological innovation capabilities.

1.3 Research framework

According to niche theory, ecology examines the interactions, roles, and functions of species within ecosystems. Key concepts in this field include foundational species, keystone species, and decomposers. Foundational species form the basic structure of ecosystems. For example, plants provide the fundamental framework for forest habitats[27]. Keystone species play central roles in ecological networks and exert significant ecological impacts. The reintroduction of wolves into Yellowstone National Park, for instance, triggered trophic cascades that affected the entire ecosystem[28]. Decomposers, such as bacteria and fungi, support energy flow and nutrient cycling within ecosystems[29]. Additionally, some species physically construct ecosystems and shape the environment. For example, multiple species collaborate to build reef habitats, creating essential structures that support diverse organisms[30].

The theory of technological niche originates from the ecological concept of "niche". It emphasizes the space for the survival and development of emerging technologies within specific environments and conditions. This space includes the positioning of new technologies in the market, their relationships with competitors, and potential user groups. Based on the technological niche theory, the current development status and competitive landscape of global smartphone technological innovation can be analyzed through four dimensions: basic niche, core niche, auxiliary niche, and architectural niche, as shown in Fig.3.

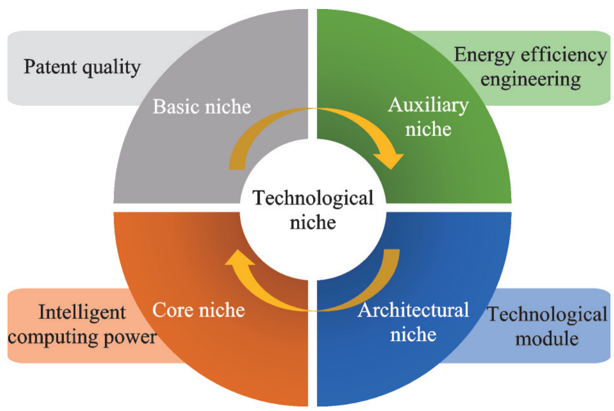

Fig.3 Research framework of this study

The basic niche defines the fundamental rules of technological evolution and entry barriers, as reflected by the patent quality of smartphone technologies. Indicators include frequently cited patents, the number of patent claims, and patents with high market value. The auxiliary niche supports technological implementation by addressing physical constraints and breakthrough solutions. This niche involves energy efficiency engineering, covering energy consumption, safety, and manufacturing processes. The architectural niche represents the hierarchical integration and cross-generational evolution within technological modules. It examines the patent layout and competitive dynamics among chip patent modules through clustering analysis. The core niche determines critical technological breakthroughs that drive market competitiveness. It is primarily reflected in the competition of intelligent computing capabilities based on AI and related technologies.

2 Global Smartphone Technological Innovation Capacity Analysis

2.1 Basic niche: Patent quality

The dataset was filtered to identify the most frequently cited patents, which were then ranked in descending order of citation frequency. As shown in Table 6, the top ten patents are all owned by companies from the United States and were granted in the United States between 2008 and 2016. The United States maintains control over the technological foundation of smartphones through fundamental patents. These patents cover areas such as wireless communication (5G/WiFi), human-machine interaction (sensor fusion), power architecture, and RF technologies. Collectively, these patents create a protective barrier of standard essential patents (SEPs). According to IPlytics data, as of 2022, the United States still accounted for 38% of global 5G SEP declarations, while the ecological penetration rate of Chinese mainland firms remains comparatively limited.

According to Table 7, Chinese mainland smartphone technology patents excel in network infrastructure. This includes areas like base station interfaces and communication protocols. The strength is evident from the number of patent claims. For instance, patents of Huawei Inc. show advanced skills in access point management. These patents feature high technical complexity and broad coverage. However, core patents for key hardware components remain limited. These components include coaxial lasers and near field communication (NFC) chips. Companies from the United States, Japan, and countries from Europe dominate these areas. Chinese mainland firms struggle with high-precision components and chip design. This reflects their reliance on foreign technologies.

According to Table 8, the most valuable patents in smartphone technology focus on wireless communication and integrated circuits. Wireless communication covers base station equipment, communication methods, and signal generation. Patsnap's evaluation highlights these high-value patents. Sun Patent Trust owns most of them. In contrast, Chinese mainland companies lack strong foundational patents in these fields. Sun Patent Trust, a patent management entity, holds many high-value patents. It profits through licensing deals or lawsuits. Xiaomi corporation (Chinese mainland), for example, has faced several patent infringement lawsuits from this entity. This situation emphasizes a key need for Chinese mainland firms. They must improve their patent strategies and risk management in the global market.

Table 6 Most cited patents in smartphone technology

Patent ID	Citation	Patent title	Patent holder
US7397364B2	1 504	Digital wireless position sensor	Webster Bio (USA)
US8103009B2	1 400	Wired, wireless, infrared, and powerline audio entertainment systems	Apple Inc. (USA)
US7853341B2	1 390	Wired, wireless, infrared, and powerline audio entertainment systems	Apple Inc. (USA)
US9099863B2	1 331	Surgical generator and related method for mitigating overcurrent conditions	Covidien LP (USA)
US9086875B2	1 065	Controlling power consumption of a mobile device based on gesture recognition	Qualcomm (USA)
US8461744B2	1 025	Rotating transducer mount for ultrasonic surgical instruments	Sirona Dental Systems (USA)
US7348875B2	1 015	Semi-passive radio frequency identification (RFID) tag with active beacon	Battelle Memorial Institute (USA)
US9368991B2	894	Distributed battery power electronics architecture and control	University of Alabama (USA)
US9325516B2	892	Power receptacle wireless access point devices for networked living and work spaces	Ubiquiti Inc. (USA)
US8457013B2	850	Wireless dual-function network device dynamically switching and reconfiguring from a wireless network router state of operation into a wireless network coordinator state of operation in a wireless communication network	Agilent Technologies (USA)

Table 7 Number of claims in smartphone technology patents

Patent ID	Claim number	Patent title	Patent holder
CN105474743B	462	Method and apparatus for establishing interfaces between access points	Huawei (China)
CN111788747B	387	Compact coaxial laser	IDEA (USA)
US8687781B2	367	Phone appliance with display screen and methods of using the same	LIN CHING YI (USA)
AU2007294728B2	329	Metering RF Lan protocol and cell/node utilization and management	Iteron Inc. (USA)
CA2993680C	240	Virtual transponder utilizing in-band commanding	Boeing (USA)
BRPI9611701B1	204	GPS receiver and method for processing GPS signals	Schneider Electric S.A. (USA)
EP3269118B8	199	Distributed radio access network with adaptive fronthaul	CommScope (USA)
US9042819B2	178	Method, system, and apparatus having NFC chip with configurable memory that is updatable via a host processor	SYNDEFENSE (Japan)
US7545867B1	156	Adaptive channel bandwidth selection for MIMO wireless systems	Marvell Asia PTE (Singapore)
CN103299437B	154	Single-photon avalanche diode (SPAD) for CMOS circuits	STMicroelectronics (Swiss)

Table 8 High-value market patents in smartphone technology

Patent ID	Patent title	Patent holder	Value (in US dollars)
CA3020241C	Method of signal generation and signal generating device	Sun Patent Trust (USA)	$13 740 000
IN533388B	Transmission method, transmission device, reception method, and reception device	Sun Patent Trust (USA)	$13 690 000
EP3952548B1	Wireless communication base station device, wireless communication terminal device, and channel allocation method	Sun Patent Trust (USA)	$13 540 000
CN103647895B	Camera body, camera system, and control method for camera body	Panasonic Corp. (Japan)	$13 520 000
US10887528B2	Information communication method	Panasonic Intellectual Property Corp. (USA)	$13 190 000
JP5823068B2	Base station device, transmission method, and integrated circuit	Sun Patent Trust (USA)	$13 160 000
JP6323737B2	Communication device, communication method, and integrated circuit	Sun Patent Trust (USA)	$13 160 000
EP3661250B1	Wireless communication integrated circuit	Sun Patent Trust (USA)	$13 140 000
JP5568748B2	Wireless communication device, wireless communication method, and integrated circuit	Sun Patent Trust (USA)	$13 050 000
JP6153014B2	Base station device, communication method, and integrated circuit	Sun Patent Trust (USA)	$13 040 000

2.2 Auxiliary niche: Energy efficiency engineering

Energy efficiency engineering highlights the competitive dynamics of smartphone technology. It integrates energy efficiency, thermal management, and process technology. This field is vital for optimizing energy use in smart devices. It respects fundamental physical limits and supports the technological niche. This study uses the Patsnap patent database. It filters data with keywords like heat dissipation modules, vapor chamber (VC) heat spreaders, low-power architectures, 3D packaging, fin field-effect transistor (FinFET), gate-all-around (GAA) transistors, thermal management, green chips, recyclable materials, and chip-level packaging. The focus is on five leading innovators: Taiwan Semiconductor Manufacturing Company (TSMC), Samsung, Qualcomm, Intel, and IBM. We apply the LSI algorithm to analyze data. Document variables come from abstracts, keywords, and texts of the latest 5 000 patent disclosures by these entities. Using energy efficiency engineering keywords as query variables, we examine the technological layout and competitive landscape. The study also compares these results with Huawei Inc. This assesses the strengths and weaknesses of Chinese mainland firms in energy efficiency engineering, as shown in Fig.4.

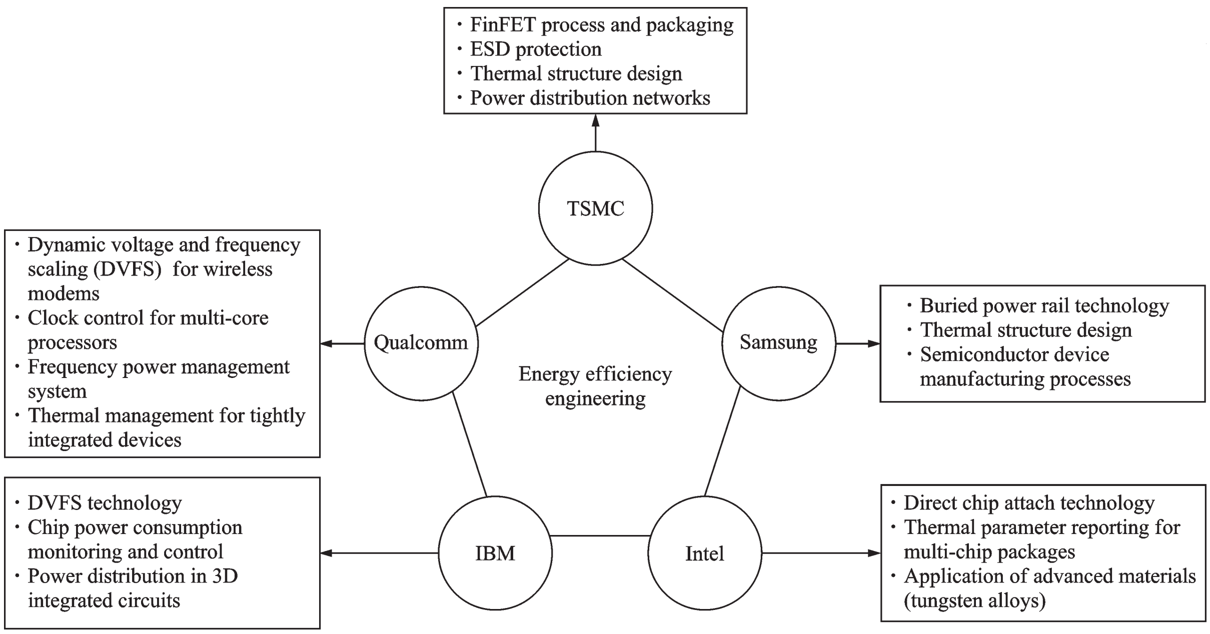

Fig.4 Technological layout of energy efficiency engineering by major innovation entities

Regarding technological depth, Qualcomm, TSMC, and Samsung are industry leaders. Qualcomm possesses a systematic and extensive patent portfolio in mobile power management. TSMC demonstrates significant patent depth in process and device technologies. Samsung holds clear advantages in power distribution and heat dissipation structures. In contrast, Huawei, as a follower, focuses on heat dissipation, with fewer patents and narrower technological scope.

In terms of technological breadth, Qualcomm, Intel, and Samsung maintain comprehensive patent portfolios, spanning device-level to system-level technologies. Samsung excels in both manufacturing processes and end-user applications. Conversely, TSMC and Huawei show narrower specialization: TSMC concentrates on manufacturing processes, while Huawei focuses primarily on end-user applications.

Therefore, Chinese mainland firms hold fewer patents in core components and exhibit notable gaps in integrated power management compared to competitors like Samsung. Their patent strategies are fragmented, achieving breakthroughs in isolated areas such as heat dissipation, but lacking comprehensive energy efficiency solutions. Additionally, these firms face limitations in key technologies, relying heavily on foreign firms for critical capabilities, including dynamic voltage frequency scaling and advanced chip manufacturing processes.

2.3 Architectural niche: Technological module

Technological module analysis measures technology concentration using indicators like patent density and technological coverage. These metrics evaluate a firm's technological focus and barriers in specific domains. By integrating LSI and IPC commonality, a three-dimensional patent map visualizes the technological landscape of smartphone chips[31]. Patent density is shown spatially on the map. Peaks denote areas of concentrated technology, while valleys indicate technological blind spots, suggesting potential opportunities or areas needing further investigation.

This study analyzes a dataset of 10 000 patents using the Patsnap patent mapping system. Selected patents are mapped onto grids, with similar patents clustered in the same or adjacent grids. The top ten innovators, grouped by country, represent four major innovation nations: The United States (Qualcomm, Skyworks Solutions, Qorvo, Apple, Intel, Avago), China (Huawei), South Korea (Samsung), and Japan (Murata Manufacturing Co., Ltd.). A comparative analysis of technological innovation capacity in smartphone chips among these entities is presented in Fig.5.

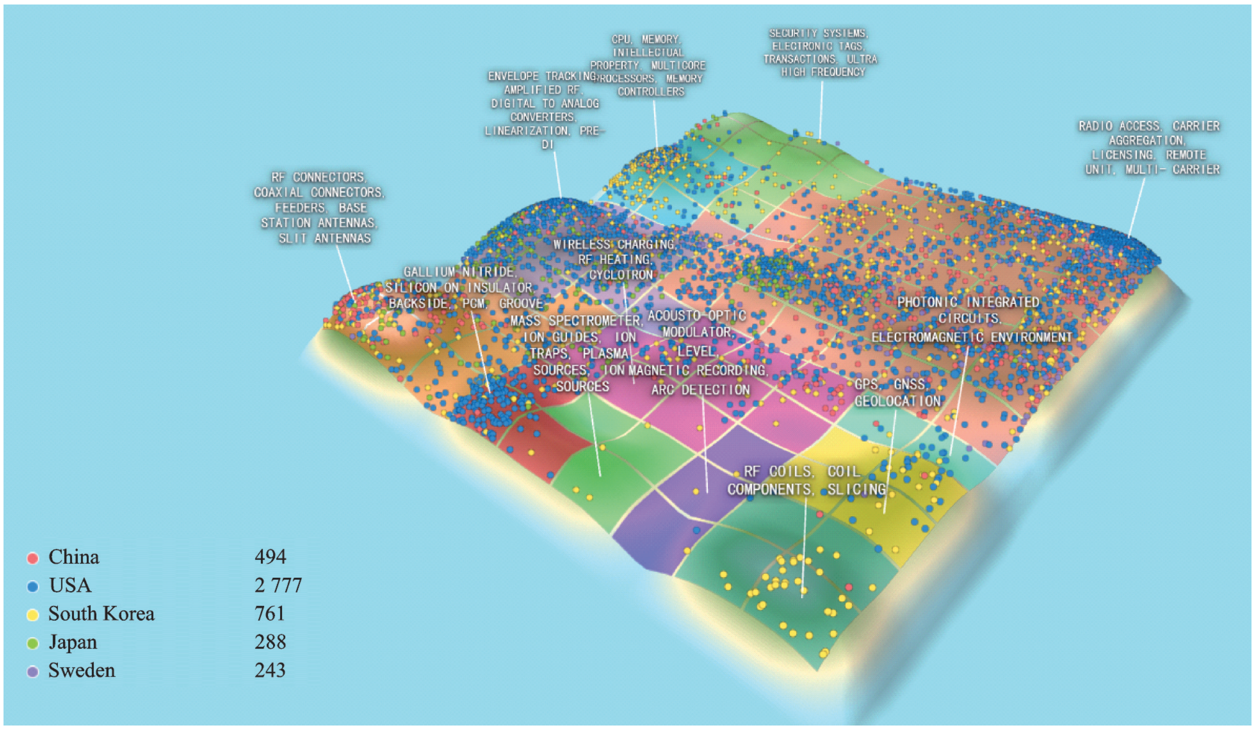

Fig.5 Technological modules of technological innovation architectural niche based on patent maps

Firstly, smartphone chip patents mainly encompass SoC, baseband, application processors, storage, wireless access, RF technology, antennas, power supplies, touchscreens, and semiconductor processes. This classification aligns with the smartphone chip categorization in Table 1. Such alignment confirms the accuracy of search expressions, IPC classifications, and other elements used in patent retrieval.

Secondly, several highly competitive technological modules, particularly wireless communication and cellular networks, encompass a total of 3 147 patents. These modules constitute the core area of competition in smartphone technology, characterized by concentrated technologies and rapid innovation cycles. Current competition focuses mainly on 5G/6G, carrier aggregation, and spectrum efficiency enhancement. Huawei, representing China, leads globally in terms of the number of 5G patents, accounting for approximately 14%. The firm has made substantial investments in both base station and terminal chip design. However, Huawei's ecosystem collaboration remains constrained due to market bans in overseas regions. Qualcomm from the United States dominates the high-end baseband chip market, with its Snapdragon platform excelling in millimeter-wave and multi-carrier technologies. Nonetheless, Qualcomm faces supply chain vulnerabilities stemming from its heavy reliance on TSMC for chip manufacturing. Apple has progressed slowly in developing its own baseband chips and continues to depend on Qualcomm's patent licensing. Despite this limitation, Apple's capabilities in software-hardware optimization partially offset its communication technology shortcomings. Samsung, from South Korea, achieves local advantages in its domestic market and select European regions through integration of Exynos chips with its own network infrastructure. However, Samsung's overall global competitiveness remains behind that of Huawei and Qualcomm.

Moreover, the fields of semiconductor manufacturing and RF hardware encompass 1 410 competitive patent technologies. Semiconductor manufacturing is marked by high levels of monopolization and substantial technical barriers. Samsung and TSMC currently lead in advanced semiconductor processes, particularly at the 3 nm and 2 nm nodes. In contrast, RF front-end modules, such as filters and power amplifiers, are mainly dominated by U.S. companies, including Skyworks and Qorvo. HiSilicon, a subsidiary of Huawei, demonstrates strong capabilities in RF integrated circuit design. However, due to sanctions, it has lost mass production capacity and has shifted its focus to breakthrough technologies, including new materials (e.g., gallium nitride) and advanced packaging methods. Qualcomm retains a leading position in millimeter-wave antenna modules, supported by its expertise in system-in-package (SiP) technology integration, although its production relies on external foundries. Apple has improved device performance through its proprietary A/M-series chips but remains dependent on external suppliers for RF hardware. To address this, it has recently invested in silicon carbide (SiC) processes. Samsung adopts an integrated device manufacturer (IDM) model, covering design, manufacturing, and storage, which enables vertical integration. Nevertheless, it still lags behind U.S. firms in advanced RF components. Japan's Murata Manufacturing Co., Ltd. focuses on multi-carrier technologies, envelope tracking, and RF coils, but continues to depend heavily on core technologies from the United States.

Finally, patent competition in the fields of the internet of things (IoT) and computer technology involves 1 232 patents. Competition in IoT focuses primarily on ecosystem integration and low-power technologies. Apple has created a closed-loop user experience through products such as AirTag (UWB tracking), the HomeKit ecosystem, and its proprietary U1 chip. However, its limited openness and cost competitiveness hinder broader adoption. Huawei, through Harmony OS and its "1+8+N" strategy, has made significant investments in industrial IoT and edge computing, though its global market expansion remains constrained. Qualcomm, leveraging its Snapdragon platform and RB3 robotics chip, has captured a substantial share in the AIoT terminal market. Nevertheless, its ecosystem integration is less developed compared to Apple. Samsung promotes device interconnectivity by utilizing its broad industry chain, spanning memory chips to smart home appliances. Despite this, it faces challenges in software experience and developer support.

2.4 Core niche: Intelligent computing power

Intelligent computing power represents innovation in the AI domain within smartphone technology. It enables breakthroughs beyond the performance limits of existing technical frameworks and serves as a driving force for niche expansion. Based on patent searches using the Patsnap database, this study investigates the technological layout and competitive landscape of major innovators in the AI domain. The analysis focuses on key AI-related areas, including deep learning, edge-side large models, tensor cores, heterogeneous computing, multimodal interaction, computational photography, accelerators, and neural networks. Using the VSM algorithm, AI-related keywords are applied as query variables to retrieve the most recent 1 000 patent documents related to intelligent computing power. These documents are treated as text variables to examine the technological distribution and competitive positioning of leading companies such as Huawei, Apple, Samsung, and Qualcomm. The study also summarizes their main research focus areas in AI-related technologies and highlights representative patents, as shown in Fig.6.

From a technological layout perspective, Huawei focuses on foundational AI technologies, encompassing areas such as speech recognition, computer vision, and deep learning. Apple specializes in optimizing intelligent assistants and improving human-computer interaction. Samsung emphasizes bio-

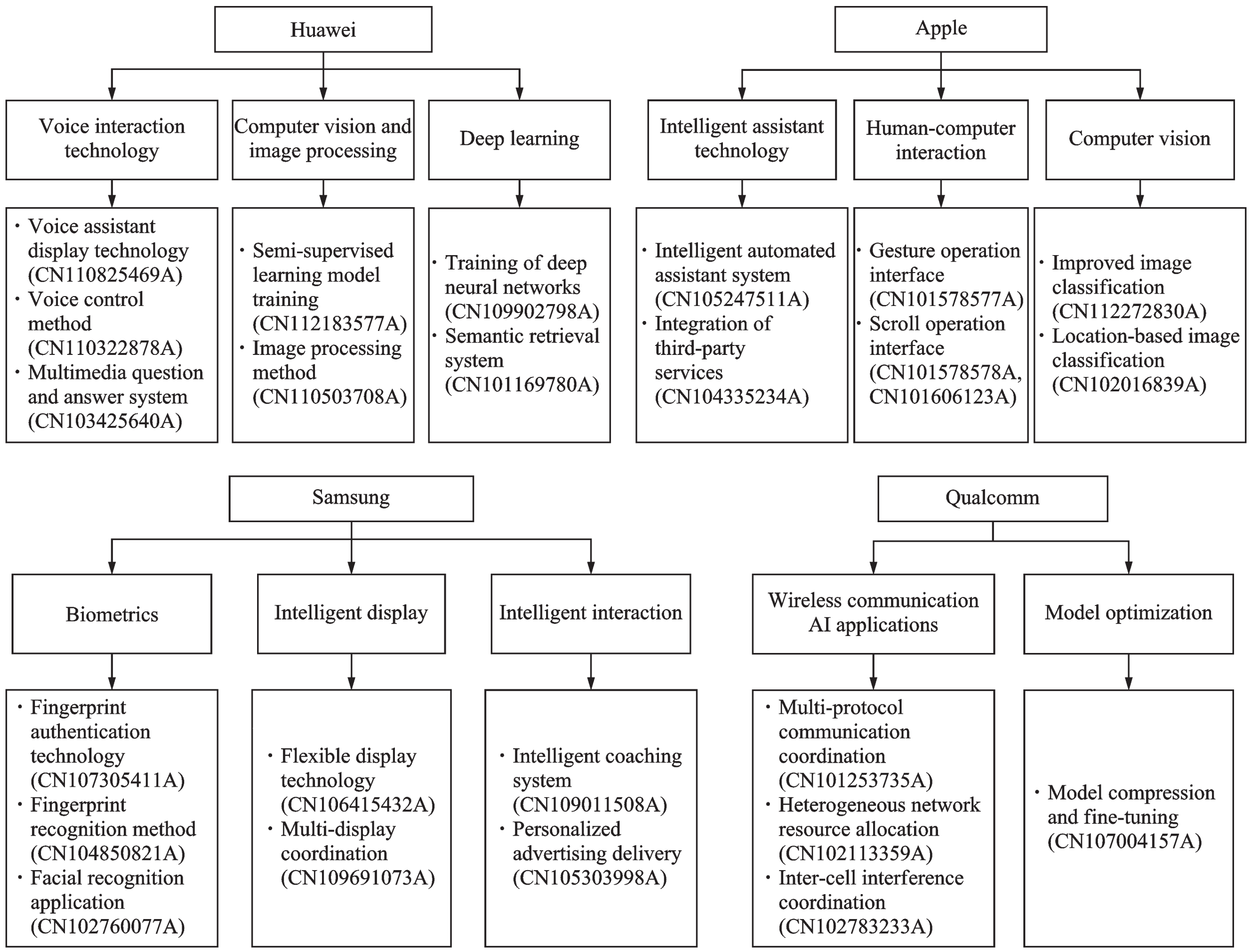

Fig.6 Competition of intelligent computing power among major innovation entities

metric recognition and smart display technologies, while Qualcomm concentrates on AI applications in wireless communication. In terms of competitive advantages, Huawei exhibits the widest coverage of AI technologies and strong capabilities in foundational research. Apple stands out in user experience design and ecosystem integration. Samsung holds notable strengths in display and biometric technologies, whereas Qualcomm excels in AI-driven communication applications.

In terms of technological competition, Huawei (voice control) and Apple (intelligent assistant ecosystem) engage in intense rivalry within the voice assistant domain, while Samsung holds a comparatively smaller market share. In computer vision, competition occurs among Huawei (semi-supervised learning), Apple (image classification), and Samsung (facial recognition). In the field of edge computing, Qualcomm (model compression) and Huawei (edge-side processing) compete for technological leadership. In interactive innovation, Apple leads in software with gesture APIs, whereas Samsung holds hardware advantages in flexible-screen interactions. Huawei and Apple also directly compete in edge-based AI applications, including image processing and voice interaction. Samsung and Apple show overlapping technological layouts in biometric fields, particularly fingerprint and facial recognition.

3 Conclusions

This study collects global smartphone patent data and uses LSI and VSM methods. Drawing on technological niche theory, it analyzes the dynamic evolution of technological niches across four dimensions: Basic niche, auxiliary niche, architectural niche, and core niche. Key indicators include patent quality, technological modules, energy efficiency engineering, and intelligent computing power. The study provides a systematic assessment of the global competitive landscape in smartphone technological innovation. The main research conclusions and insights are as follows:

(1) In terms of patent quality, the United States has established a strong technological foundation through the acquisition of high-value patents. It holds standard-essential patents (SEPs) in key areas such as wireless communication and integrated circuits, thereby creating global barriers to market entry. Chinese mainland firms continue to show weaknesses in patent family size and claim breadth. In particular, they remain highly dependent on external technologies for core communication protocols and high-precision components. Additionally, Chinese mainland firms need to improve their patent risk management mechanisms to reduce exposure to overseas litigation risks.

(2) In terms of energy efficiency engineering, companies such as Qualcomm and TSMC have developed comprehensive patent portfolios covering power management and process technologies. In contrast, Chinese mainland firms tend to focus on single-point technologies, such as heat dissipation structures. They lack integrated solutions for energy efficiency optimization across components and systems. Moreover, high-end chip manufacturing in China remains dependent on external supply chains. As a result, Chinese mainland firms should enhance the development of core power management technologies, including dynamic voltage and frequency scaling algorithms. In addition, fostering collaboration among industry, academia, and research institutions is essential to achieve breakthroughs in advanced process technologies, such as GAA transistor technology.

(3) In terms of technological modules, Huawei holds a leading position in 5G communication modules. However, its participation in overseas ecosystems remains limited. The semiconductor manufacturing sector is largely dominated by TSMC and Samsung, while RF components continue to depend on American suppliers. To address these challenges, Chinese mainland firms must pursue technological substitution through innovations in new materials, such as gallium nitride, and advancements in packaging technologies. Furthermore, promoting the reconstruction of technological systems through an "open-source architecture + modular design" approach, illustrated by the reduced instruction set computer-Five (RISC-Ⅴ) ecosystem, is essential for reducing reliance on advanced RISC machine (ARM) and X86 architectures.

(4) In terms of intelligent computing power, Huawei leads in the scope of AI foundational technology coverage, while Apple maintains a competitive edge in user experience through its integrated hardware-software ecosystem. Chinese mainland firms still face challenges in bridging collaboration gaps among computing power, algorithms, and application scenarios, especially in advanced areas such as edge-side large models and heterogeneous computing. To address these challenges, adopting a "scenario-driven" approach to technology development is crucial, with a focus on differentiated sectors such as industrial IoT and smart devices. Additionally, building a closed-loop ecosystem that integrates "hardware + operating system + developer community", modeled after the Harmony OS, is essential for enhancing technological competitiveness.

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Authors

The first author Mr. **ZHANG Yuwen** received his B.S. and M.S. degrees in management from Jiangsu University of Science and Technology in 2010 and 2014, respectively. He is currently pursuing a Ph.D. degree in management at Nanjing University of Aeronautics and Astronautics. His research focuses on intelligence research, patent analysis, and related fields.

The corresponding author Prof. **CHEN Wanming** received his M.S. degree in 1984 and Ph.D. degree in 1998, respectively. He was appointed as a professor in 1999 and became a doctoral supervisor in 2002. He is an expert who enjoys the State Council's special government allowances. His research focuses on intelligence consulting, intelligence analysis, and related fields.

Author contributions Mr. **ZHANG Yuwen** contributed to data and model components for the LSI and VSM, conducted the analysis, and wrote the manuscript. Prof. **CHEN Wanming** designed the study, interpreted the results and contributed to the discussion and background of the study. Both authors commented on the manuscript draft and approved the submission.

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基于潜在语义索引与向量空间模型方法的全球智能手机技术创新力分析

张裕稳，陈万明

（南京航空航天大学经济与管理学院，南京 211106，中国）

摘要：运用潜在语义索引(Latent semantic indexing, LSI)与向量空间模型(Vector space model, VSM)方法，对全球智能手机技术创新力的竞争格局进行了系统分析。本研究融合技术生态位理论，从专利质量、能效工程、技术模块和智能算力4个核心维度进行评估。研究结果表明，美国通过无线通信和集成电路领域的标准必要专利(Standard-essential patents, SEPs)构建了坚固的技术壁垒；相比之下，中国大陆企业在核心基础技术方面仍存在较大依赖。美国高通公司与中国台湾台积电公司在能效工程领域构建了系统完备的专利组合，而中国大陆在动态频率调节算法与高端制造工艺方面仍面临技术突破的挑战。中国大陆的华为公司在5G模块技术方面处于领先地位，但在生态系统协同方面仍显不足，半导体制造与射频(Radio frequency, RF)组件依赖外部供应商的现状，凸显出新材料与开源架构创新的紧迫需求。为提升智能算力水平，中国大陆企业需应对协同整合难题，推动以应用场景为导向的技术战略，构建涵盖硬件、操作系统及开发者网络的综合生态系统。

关键词：智能手机芯片；技术创新力；潜在语义索引；向量空间模型